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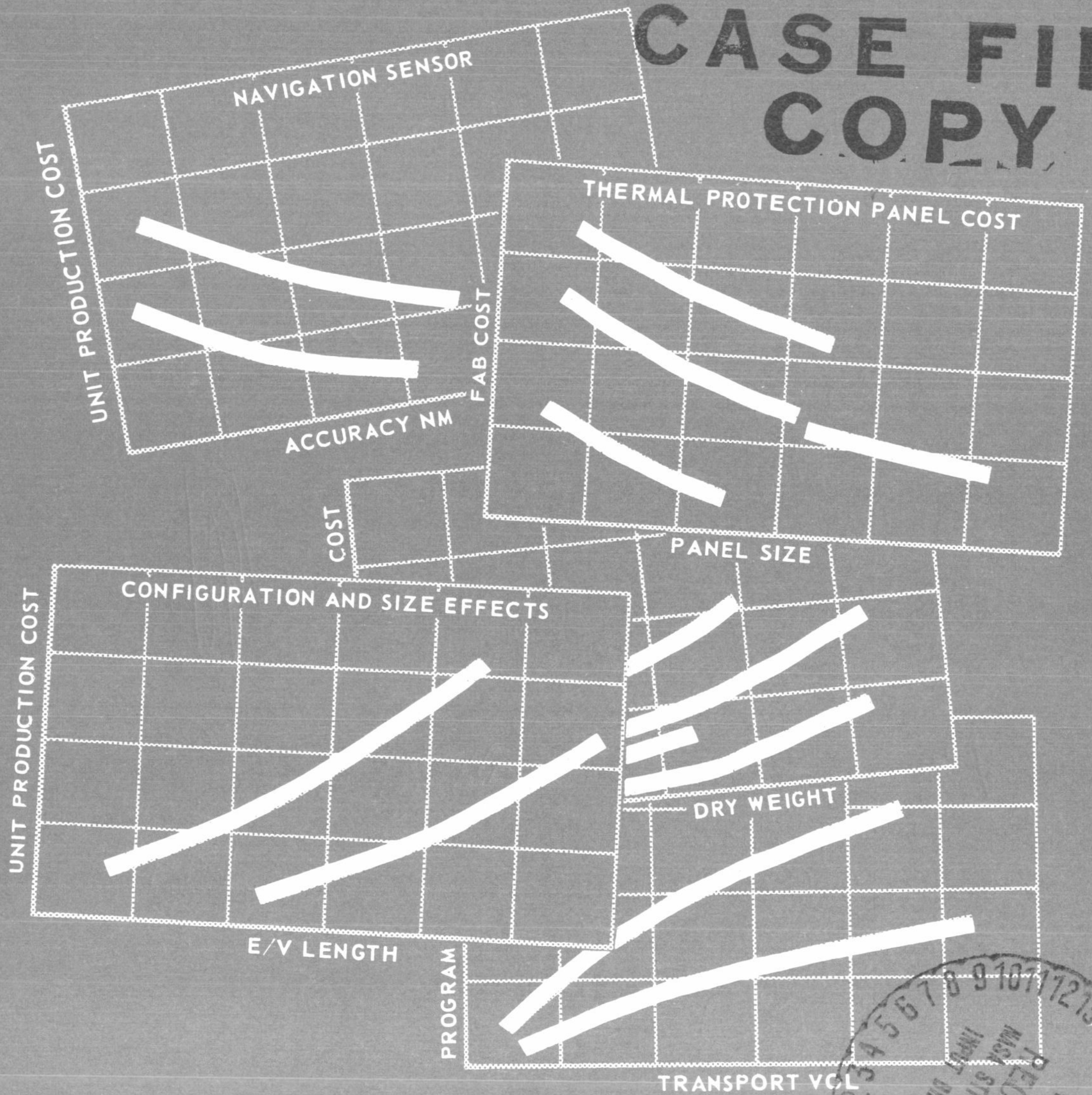
OPTIMIZED COST/PERFORMANCE DESIGN METHODOLOGY



VOLUME II DATA REVIEW AND ANALYSIS
BOOK 5 - COST
CONTRACT NAS 2-5022

MCDONNELL DOUGLAS CORPORATION

REPORT G975

15 APRIL 1969

SERIAL NO. 89

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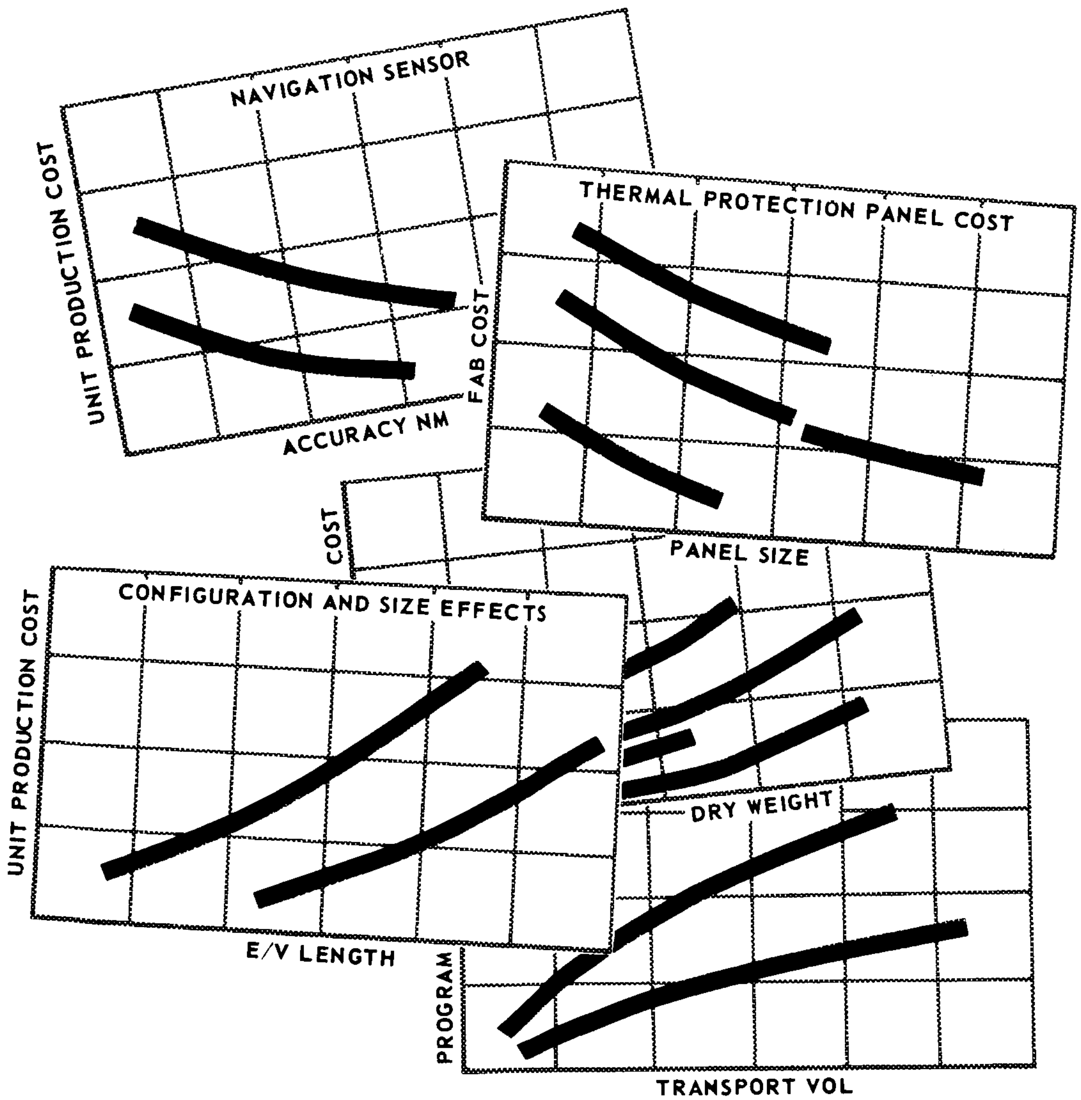

VOLUME II DATA REVIEW AND ANALYSIS

BOOK 5 - COST

CONTRACT NAS 2-5022

MCDONNELL DOUGLAS CORPORATION

FOREWORD

This report is submitted to NASA, the Mission Analysis Division of OART, as part of the final reporting on Contract NAS 2-5022, Optimized Cost/Performance Design Methodology of Orbital Transportation Systems. This twelve month study was initiated in July 1968 and was performed in two general phases: a data review and analysis phase and a system evaluation phase. The reporting of the study is organized in three volumes but includes several books in Volumes 2 and 3. Volume 1 is a short summary of the complete study, Volume 2 covers the phase 1 data review and analysis, and Volume 3 covers the phase 2 system evaluation. The Study Manager was L. M. McKay; the major Task Leaders were P. T. Gentle, V. E. Henderson, L. E. Smith, and A. D. Trautman. The NASA Technical Monitor was C. D. Havill.

McDonnell Douglas gratefully acknowledges the support and cooperation of many companies which supplied information to the study. A list of the companies and their area of contribution is included in Appendix A.

ABSTRACT

The broad objectives of this study were to gather historical cost and performance data, organize and analyze the data so that cost estimating relationships could be developed, and evaluate several system concepts for space logistics support.

The primary source of historical cost data was the Gemini and Saturn Programs and cost estimating relationships draw extensively on this experience. A range of reuse concepts were evaluated and optimum (least cost) concepts defined for a variety of program options. These include variations in such things as crew size, cargo capacity, program requirements, etc. for either ballistic or lifting body (M2-F2) entry vehicles.

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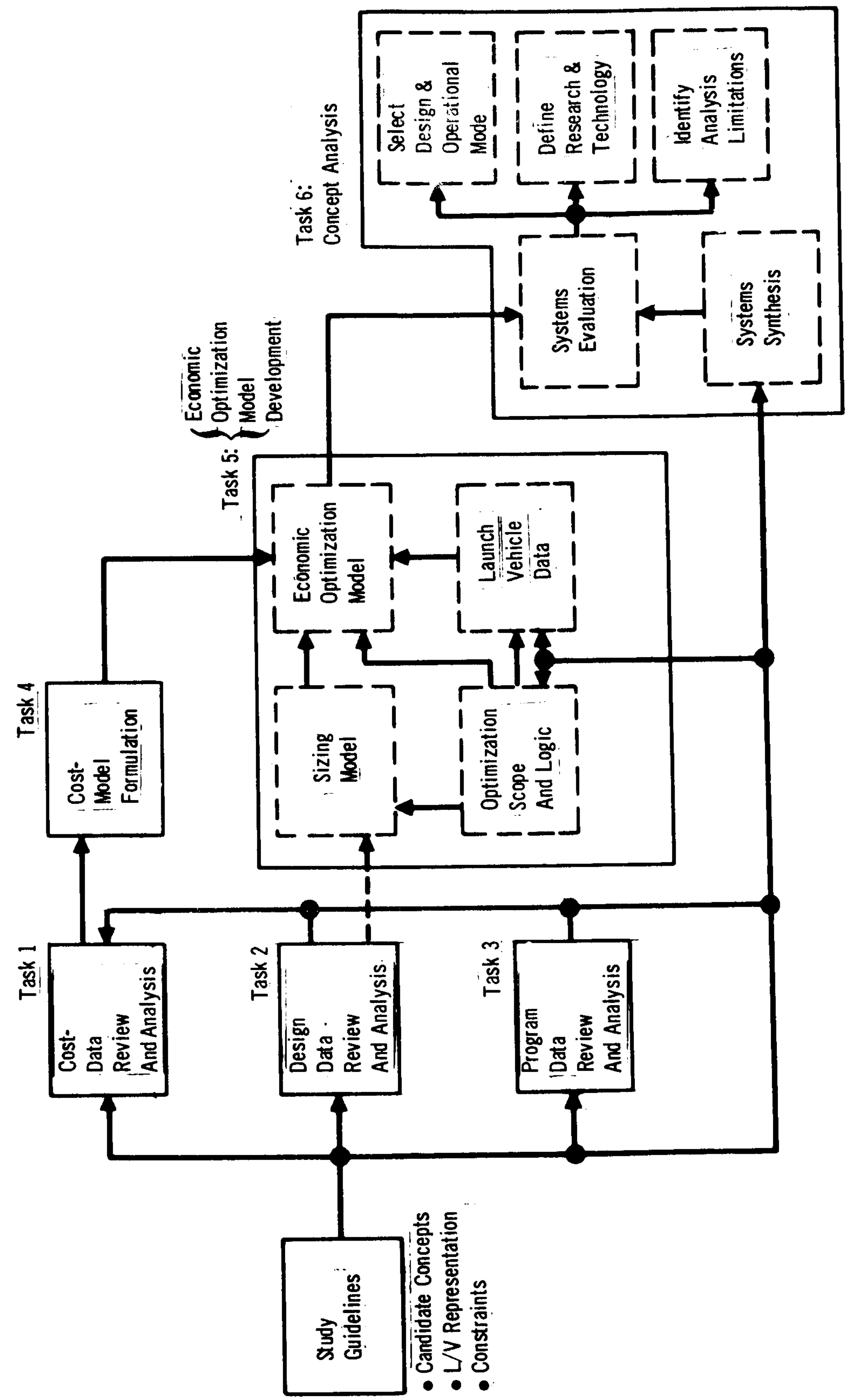
1. INTRODUCTION - The purpose of the Optimized Cost/Performance Design Methodology study was to provide a method of using cost as a basic design parameter in identifying and defining more economical space transportation systems. This study was performed in six tasks as shown in Figure 1-1. Task 1 involved developing the cost data, organizing the data by categories, and developing cost estimating relationships. Tasks 2 and 3 developed the requirements and the physical and functional characteristics of the alternate spacecraft subsystems and operations. An analytical cost model was formulated in Task 4. Task 5 developed the logic, data, and methods for systematically varying the design and operational specifications of each vehicle configuration. Task 6 took all the data and tools developed in the other tasks and then determined the economically optimum design and operational philosophies, sensitivities to program size, launch rate, payload size, the problem areas and technology limitations.

This book reports on the work accomplished in Task I. The objectives of this task were to:

1. Define a cost element structure (CES) for the purpose of cataloging and identifying cost history and formating the cost model.
2. Organize the cost history from the Gemini program and the Saturn S-IVB program into the cost element structure.
3. Develop cost estimating relationships (CER's) from the available cost history and vehicle physical and functional characteristics.

Figure 1-1

STUDY TASK FLOW



2. SUMMARY - This book contains a discussion of the efforts and analysis of Task 1, Cost Data Review and Analysis. The objectives of this task were to gather, organize, and normalize cost data from historical programs so that cost scaling relationships could be developed to estimate the cost of future systems. The major subtasks therefore were to develop a cost element structure, organize the historical cost data from the Gemini and S-IVB programs according to this structure, and then using these data plus a variety of other data, develop the cost estimating relationships.

The cost element structure groups the data into a development phase, an investment phase, and an operational phase. The development phase was defined to include five flight tests; the historical data from Gemini and S-IVB were adjusted to reflect this assumption. Other adjustments which were required to normalize the data included adjustments in labor rate and inflation factors, transfer of some charges from one labor category to another, etc. All costs assume a 1969 dollar base.

In developing the cost estimating relationships, a major goal was to incorporate design parameters into the equations so that cost can be used as a basic design parameter. Therefore the CER's are written at a very detailed level, in general at the subsystem or subsystem component level. Cost and performance/design data were solicited from a number of companies as a means of enhancing the validity of the study. A list of those who contributed is contained in Appendix A. The emphasis of the study was on the spacecraft but, to estimate total program costs, general cost trends were developed at the total system level for several classes of launch vehicles.

The final task of the study is an analysis of a range of reuse concepts from fully expendable to fully recoverable space vehicles with both a ballistic and a lifting body entry vehicle. Some of the CER development was necessarily tailored to the peculiarities of these concepts and an understanding of the concept definition is helpful. The progression of the concepts from expendable (Category A) to reusable (Category F) is shown in Table 2-1. This applies to both configuration I, the ballistic, and configuration II, the lifting body.

Section 3 of this report contains the ground rules and assumptions that have been applied in the cost analysis, Section 4 describes the data

sources, Section 5 explains the data organization and analysis. Section 6 discusses the CER development and Section 7 describes development of the launch vehicle cost trends.

Table 2-1

Reuse Category Summary

Category / Component	Expendable	Partially Reusable				Reusable
	A	B	C	D	E	F
Entry Vehicle	E	R	R	R	R	R
Maneuver Propulsion/ Cargo Module	E	E	R	R	R	R
Upper Stage Engines	E	E	E	R	R	R
Upper Stage Tanks	E	E	E	E	R	R
First Stage	E	E	E	E	E	R

E - Expendable R - Reusable □ Integral

3. COST ANALYSIS GROUND RULES AND ASSUMPTIONS - The following ground rules and assumptions were established to govern the organization and analysis of the historical cost data and the development of the Cost Estimating Relationships (CER's) for the cost model.

1. The historical cost data to be utilized will include Gemini and Saturn S-IVB. Additional cost history as available from Mercury, Asset, military aircraft, commercial aircraft, previous studies, and vendor requested data will be incorporated.

2. A cost Element Structure (CES) will be developed for the purpose of cataloging and identifying the cost history and formating the cost model.

3. The cost history from the Gemini and Saturn S-IVB programs will be organized and reported in accordance with the CES.

4. The Gemini program cost data defined in the cost element structure shall reflect a five flight test program. Development of the cost for the 5 vehicles and flights from the cost history of 12 vehicles shall be based on the unit cost and the appropriate learning curves.

5. The Saturn S-IVB Cost Data Analysis will employ the SAT-V configuration in order to account for SAT-IB/SAT-V common effort charged to SAT-V by NASA ground rule. The RDT&E phase of the Saturn S-IVB program will be defined as the time period from contract inception (June, 1962) to delivery of the fifth test stage from the Sacramento Test Center (7/27/66). This includes 4 SAT-IB stages and 1 SAT-V stage, the total of 5 being comparable to that used in defining the Gemini RDT&E phase. The SAT-IB stages are included due to their scheduling prior to SAT-V and to avoid an unrealistically long RDT&E phase which would result from selection of all SAT-V stages. Flight test operations associated with the S-IVB RDT&E phase will be accounted for separately from all other costs due to abnormal elapsed time between delivery and launch of stages four and five which resulted from problems with the payload and other stages of the launch vehicle. S-IVB procurement for the RDT&E

and investment phases will be determined in terms of a theoretical 1st unit cost for the SAT-V configuration along with recommended learning curves to be applied to each procurement cost category for quantity extensions.

6. The following mid-calendar 1969 labor rates which include direct labor, overhead, G. & A. & overtime premium (but exclude fee) shall be employed in translating man-hour estimates into cost.

	In-Plant	Remote Site
Engineering and Testing	$20.00/hr	$20.00/hr
Production (including planning and quality assurance)	$11.80/hr	$13.00/hr
Tooling	$13.40/hr	
Remote Site Composite Rate		$16.00/hr

Remote site labor rates are based on a composite labor rate consisting of engineering and production.

7. All other program costs shall be adjusted to mid-calendar 1969 dollars using a 5% annually compounded factor.

8. A 10% fee is to be used at the program phase level.

9. A 1963 technological base shall be assumed for both the Gemini and Saturn S-IVB programs and the provision shall be made in the cost model for the inclusion of a technology escalation factor to be applied to all RDT&E phase costs except system test hardware procurement and major subcontractors. This annually compounded factor should account for the increased documentation, test requirements, quality assurance and related type efforts which are imposed on a program as a function of time and tend to increase its complexity.

4. COST DATA SOURCES AND DESCRIPTIONS - Although the emphasis of this study is directed toward cost data for advanced spacecraft, many data sources have been used. These include several space programs, aircraft data, data solicited from subsystem manufacturers, and data from previous studies.

4.1 Space Programs - The primary sources of data for the whole study were the Gemini and Saturn IVB programs. Some limited data were obtained from the Mercury and ASSET programs, but these were special data points; the Mercury and ASSET data were not analyzed in the same detail as the Gemini and Saturn data.

4.1.1 Gemini Program - The following paragraphs outline the Gemini program history and cost accounting system. The subsystem design characteristics of the Gemini are included in Volume II Book 1 Appendix C.

4.1.1.1 Gemini Program History - In April of 1961, the National Aeronautics & Space Administration (NASA) authorized MDAC to begin an engineering study program to develop alternate concepts of design and arrangements which would carry on the United States manned space flight program accomplished by the Mercury program. This study was performed under NASA Contract No. NAS9-119. The vehicle studied was designated the Mark II Mercury spacecraft and was similar to the Mercury capsule but was for two men and approximately 50 percent larger in volume. On 15 December 1961, NASA notified MDAC that it had been selected to design and manufacture the two-man spacecraft to be named Gemini. Engineering go-ahead was authorized on 23 December 1961 and the formal contract was executed on 29 March 1963. The Gemini program was performed under NASA Contract No. NAS9-170. Project Gemini was to develop the capability to rendezvous and dock with a moving target vehicle, to attain a new orbit through the use of the target vehicle's propulsion system, to carry out extravehicular activity, to perform useful work in space, and to demonstrate a two-man life support capability for space missions of up to 14 day's duration. The above goals were accomplished.

As defined by NASA, the MDAC role in the Gemini program was to design and manufacture a two-man entry vehicle, a launch adapter module, a target docking adapter, trainers, training aids, and simulators to ensure crew familiarity with the spacecraft systems and procedures. Static articles and boilerplate modules were to be furnished for use in an intensive test program. A detailed description of the development program can be found in Volume II Book 2.

The hardware finally supplied by McDonnell under the Gemini Contract comprised the following:

	Entry Module	Adapter Module
S/C No. 1 Unmanned Flt.	1	1
Adapter 1A (Spare)	-	1
S/C No. 2 Unmanned Flt.	1	1
S/C No. 3 Manned Flt.	1	1
S/C No. 3A Thermal Qual. (Ground test)	1	1
S/C No. 4 through 12 Manned Flt.	9	9
Total	13	14

6 Agena Target Docking Adapters (TDA's)
2 Mission Simulators
1 Translation and Docking Trainer
5 Boilerplate Entry Modules
4 Static Entry Modules
4 Static Launch Adapters
2 Static TDA's
2 System Test Units
  (Electronic System Test Unit, ESTU)
  (Compatibility Test Unit, CTU)
1 Egress Trainer
1 Crew Station Mock-up Trainer
1 Centrifuge Trainer
1 TDA Electrical Simulator
1 Spacecraft Simulator
1 Electrical and Sequential Training Panel
1 Attitude and Maneuvering Control System Trainer
1 Ejection Seat Trainer

The contract also specified that MDAC support NASA operations at Cape Kennedy and supply personnel in support of the mission simulators and the translation and docking trainer located at the Manned Spacecraft Center, Houston, Texas.

In October 1963, the Space Systems Division of the U.S. Air Force authorized MDAC to study integrating experimental hardware items into the Gemini missions. From these initial studies evolved the Gemini experiment program, which began in December 1963 with the incorporation of three DOD experiments into the mission plans for Spacecraft 3. On that first manned flight of the Gemini series, two scientific experiments (sea urchin egg growth and radiation effects on blood) and one technical experiment (reentry communications) were performed. All subsequent missions carried experimental equipment - in all, 53 different experiments were flown on 10 manned Gemini missions. All experimental incorporations were performed under NASA Contract No. NAS9-170. The type and quantitities of experiments performed are outlined below.

Type		Number of Experiments
Medical		8
Engineering		10
Technical		3
Defense		15
Scientific		17
	Total	53

A supplement to the Gemini contract was negotiated on 28 January 1965. The cost-plus-fixed-fee contract was converted to a cost-plus-incentive-fee plan. Under the new terms of the contract, MDAC was to be rewarded for meeting or improving upon the delivery schedule, for high performance of the spacecraft and its subsystems, and for cost reduction. These provisions were made retroactive to 1 April 1964. Some indication of how successfully MDAC was able to perform under the new agreement may be derived from the fact that the schedule delivery date for Spacecraft 12 was 25 October 1966, actual delivery was made on 6 September 1966.

Twelve missions were flown during the Gemini Program. All spacecraft were launched from Complex 19, Cape Kennedy, Florida with a modified Titan II ICBM, "man-rated" for Gemini usage. A synopsis of each mission is contained in Appendix B.

4.1.1.2 Gemini Cost Accounting System - The cost accounting system for the Gemini Program consists of three MDAC Job Order numbers for the NASA Contract Number NAS 9-170. These are:

Job Order 306 - Design and fabrication of the hardware items outlined in Paragraph 4.1.1.1.

Job Order 356 - Remote base operations at Cape Kennedy and Houston, Texas.

Job Order 383 - Incorporation of the DOD experiments into the Gemini Program.

Job Order 306 is divided into additional elements which are identified by item numbers and cost codes. Table 4-1 presents a summary of the item numbers and titles. The item numbers identify the spacecraft subsystems and the necessary support and integration effort. Since many of the subsystems were subcontracted by MDAC to other companies, Table 4-1 also outlines, by subsystem, the companies with the primary and secondary responsibilities. MDAC as the prime contractor was, of course, responsible for all subsystems and the integration of these subsystems into the spacecraft. Only the major subcontractors are listed.

As outlined above the item numbers segregate the cost by spacecraft subsystem and the necessary support areas. Each item number is further segregated by a cost code that defines a task category. The cost codes consist of functions such as design, design support, testing, wind tunnel, mock ups, production cost by spacecraft, etc. These task categories (cost codes) are too numerous to outline here but generally can be grouped as follows.

1. Cost Codes 001 through 199 - General and Support
2. Cost Codes 200 through 399 - Engineering Division Responsibilities
3. Cost Codes 400 through 499 - Tooling Division Responsibilities
4. Cost Codes 500 through 699 - Production Division Responsibilities

Each of the above item numbers and cost codes record the expenditures of each division of the company and each department in that division. The cost history available is therefore segregated by spacecraft subsystem, task, division of the company, and department.

Table 4-1

GEMINI PROGRAM ITEM NUMBERS		
Item Number Description	Primary Responsibility	Secondary Responsibility
Support and Integration Items		
01 Flight Technology & Mission Planning	NASA	MDC
02 Trainers & Simulators	MDC	BURTEK
03 Personnel Training	NASA	MDC
04 Ground Test Program	MDC	
05 Thermal Qualification Test	MDC	
06 Spacecraft Systems Test (SST)	MDC	
07 Launch Operations (St. Louis Support)	MDC	
08 Publications	MDC	
09 Spares	MDC/Major S/C	
10 Spacecraft Refurbishments	MDC	
11 AGE	MDC/Major S/C	
12 Maintenance GOE	MDC	
13 Specifications & Documentation	MDC	
Entry Vehicle Items		
21 Entry Vehicle Structure	MDC	
22 Entry Vehicle (Final Assembly)	MDC	
23 Inertial Guidance System	Honeywell, IBM	
24 Attitude Control System	Honeywell	
25 Electrical System	MDC	
26 Communication System	Collins, EMR	
27 Instrumentation & Recording	MDC	
28 Reaction Control System (RCS)	Rocketdyne	
29 Paraglider	-	
30 Recovery Parachute	Northrup Ventura	
31 Post Landing & Survival Systems	MDC	
32 Crew Systems, Displays, & Instruments	MDC	Lear
33 Ejection Seat	Weber	
34 Time Reference System	MDC	
35 Pyrotechnics & Release Mechanisms	MDC	
36 Environmental Control System (ECS)	Airesearch	
37 Ablation Shield	MDC	
56 Rendezvous Radar	Westinghouse	
57 Horizon Sensor	A.T.L.	
Adapter Module Items		
51 Adapter Module Structure	MDC	
52 Adapter Module (Final Assembly)	MDC	
53 Fuel Cell	General Electric	
54 Reactant Supply System (RSS)	Airesearch	
55 OAMS (Adapter Propulsion System)	Rocketdyne	
59 Retrograde	Thiokol	
61 Adapter ECS	MDC/Airesearch	
62 Electrical & Misc. Electronics	MDC	Motorola
Target Adapter		
71 Target Vehicle Docking Adapter (TVDA)	MDC	Westinghouse
72 Simplified Target Vehicle	MDC	

Job Order 356, Remote Base Operations, is also segregated by item number and cost code. The item numbers are outlined below.

01. Spacecraft No. 1
02. Spacecraft No. 2
03. Spacecraft No. 3
04. Spacecraft No. 4
05. Spacecraft No. 5
06. Spacecraft No. 6
07. Spacecraft No. 7
08. Spacecraft No. 8
09. Spacecraft No. 9
10. Spacecraft No. 10
11. Spacecraft No. 11
12. Spacecraft No. 12
13. Augmented Target Docking Adapter
20. Facility Activation
25. Cape Kennedy Participation in Gemini Mission No. 1A
28. General Support Services
30. Gemini Program Indoctrination
40. Miscellaneous NASA Services for Other Contractors
50. Design and Fabrication of AGE
60. Special Support Programs - NASA
61. Subcontractor Field Support - Cape Kennedy, Florida
70. Specific Support Programs
71. Spare Parts
72. Ground Support Equipment Items - Major
73. Ground Support Equipment Items - Miscellaneous
74. Facility Maintenance and Support
75. Research and Development
76. Future Program Preparations
77. Mission Simulator
78. NASA Support
79. MDAC Support
80. Material for Cape Kennedy
81. Direct Charges for Cape Kennedy - Includes Travel and Per Diem

Houston Operations

92. Operations, Houston, Texas

93. Houston, Texas Support Activities - Gemini Trainers

The detailed accounting of the expenditures covers only Gemini 5 through 12 because early in the program all of the expenditures were recorded against one cost number. However, about the time Spacecraft 5 was delivered to the Cape industrial area, the above accounting system was instituted.

4.1.2 Saturn S-IVB Stage - The LO_2/LH_2 (J-2 engine) S-IVB is used as a second stage of the Saturn IB launch vehicle and as a third stage of the Saturn V vehicle. Its development program was initiated in late 1961 with a preliminary design study. Initially, the stage was to be used only on the Saturn V vehicle with ground testing (battleship and all-systems) scheduled from mid 1963 thru mid 1965, and the delivery of flight stages commencing in early 1965. It was subsequently decided to replace the S-IV stage on the Saturn I vehicle with the S-IVB, to increase its performance capability. The new vehicle was named Saturn IB. Preliminary design on the S-IVB for this application was begun in late 1962. The introduction of the second S-IVB configuration resulted in a modification to the original ground test program and delay in delivery of flight stages. Since the Apollo development program required the Saturn IB launch vehicle prior to the Saturn V, three S-IVB/IB stages were delivered and flown (1966) prior to the first Saturn V launch (late 1967). A detailed description of the development program for this stage can be found in Book 2 of this volume.

Since one of the purposes of examining the historical costs of this program was to provide data for constructing cost estimating relationships, only that portion of the data associated with a single configuration was desired. The Saturn V configuration was selected for this purpose since all effort "common" to both configurations had been charged to this configuration. The S-IVB stage was an outgrowth of the Saturn S-IV stage which further tends to distort the design and development cost data since the amount of carryover and resulting cost reduction is unknown.

The subsystem design characteristics of the S-IVB/V stage configuration are contained in Volume II Book I Appendix B.

4.1.3 Mercury Program - The objectives of Project Mercury were to put a manned spacecraft into a controlled orbit around the earth, to investigate man's performance capabilities and his capacity to withstand the environment of space, and to test and successfully recover the spacecraft.

The selection of McDonnell Aircraft to build the Mercury Spacecraft was announced on 15 January 1959; Contract NAS 5-59 for the construction of 12 manned orbital spacecrafts, was signed by McDonnell on 13 February 1959. Subsequent amendments to the contract added eight additional spacecrafts, two on 1 February 1960 and six on 24 May 1960. Two Procedural Trainers and one Environmental Trainer became contract additions on 1 February 1960. Seven Check-out Trailers were added on 31 August 1960.

The cost accounting system is not discussed since only a limited amount of cost data was available for the study. Available time and manpower precluded the analysis and organization of the Mercury cost data into the cost element structure.

4.1.4 ASSET Program - The only data utilized from the ASSET program was the structural design cost, therefore, a description of the ASSET program is not presented.

4.2 Aircraft Programs - Available aircraft data was employed in the CER development. Detailed cost history from the F-4 Phantom II fighter aircraft was used extensively in the analysis with a limited amount of cost history from other aircraft.

4.3 Vendor Supplied Cost Data - Vendor supplied cost data was utilized when the data was considered reasonable and applicable to the particular subsystem under analysis.

The following companies provided cost and performance data.

Supplier	Subsystem
Aerojet-General	Propulsion
Airesearch	Power Supply
Allis-Chalmers	Power Supply
Barnes Engineering	Avionics
Bendix Corporation	Environment Control
Collins Radio Company	Avionics
Hamilton Standard	Environment Control

Supplier	Subsystem
Honeywell, Inc.	Avionics
IBM	Avionics
Leach, Inc.	Avionics
Marquardt	Propulsion
Motorola	Avionics
Pratt and Whitney Aircraft	Power Supply
Pratt and Whitney Aircraft	Propulsion
Rocketdyne	Propulsion
Spacecraft, Inc.	Avionics
Sundstrand Aviation	Power Supply
TRW, Inc.	Avionics
Westinghouse	Avionics

4.4 Studies - Cost data and/or cost models from the following contracted studies were also utilized in constructing the cost program for this study.

4.4.1 Design Considerations of Reusable Launch Vehicles, Final Report, report numbers DAC-57912 thru DAC-57917, October 1966, contract No. NAS2-3191. Cost program and vehicle descriptions used to generate cost-performance relationships for lifting body launch vehicles.

4.4.2 Improved Launch Vehicles for Spacecraft or Near Term Launch Vehicle Concepts (Expendable Rocket), Report No. DAC-57990, April 1967, contract No. AF04(695)-995. Cost program used to define cost-performance relationships for expendable launch vehicles.

4.4.3 Multipurpose Reusable Spacecraft Preliminary Design Effort (Category A), Report No. DAC 58072, November 1967, contract No. AF04(695)-67-C-0125. Cost data and relationships used in new spacecraft model.

4.4.4 Multipurpose Reusable Spacecraft Preliminary Design Effort, MDAC Report F749, dated October 1967.

5. COST DATA ORGANIZATION AND ANALYSIS - This section presents the Cost Element Structure (CES) that was developed for this study, the cost history for the Gemini and S-IVB programs, and the necessary adjustments required to organize the cost history according to the CES.

5.1 Cost Element Structure - The cost element structure (CES) provides the bookkeeping format for identifying and tracking the various costs associated with system development, investment, and operation. Also, it provides the format for the cost model. The CES was developed on the basis of the cost history available and the objectives and requirements of the OCPDM study. The following paragraphs outline each of the cost areas by program phase.

5.1.1 Total Program Cost - The CES is divided into 5 major phases and 2 major projects as shown in Figure 5-1 and discussed in the following paragraphs.

I. Program Phases:

A. Preliminary Analysis - Corresponds to phased project planning Phase A conducted inhouse by NASA to establish feasible project concepts for detailed study. Cost is not to be included in present model, and is included here for reference only.

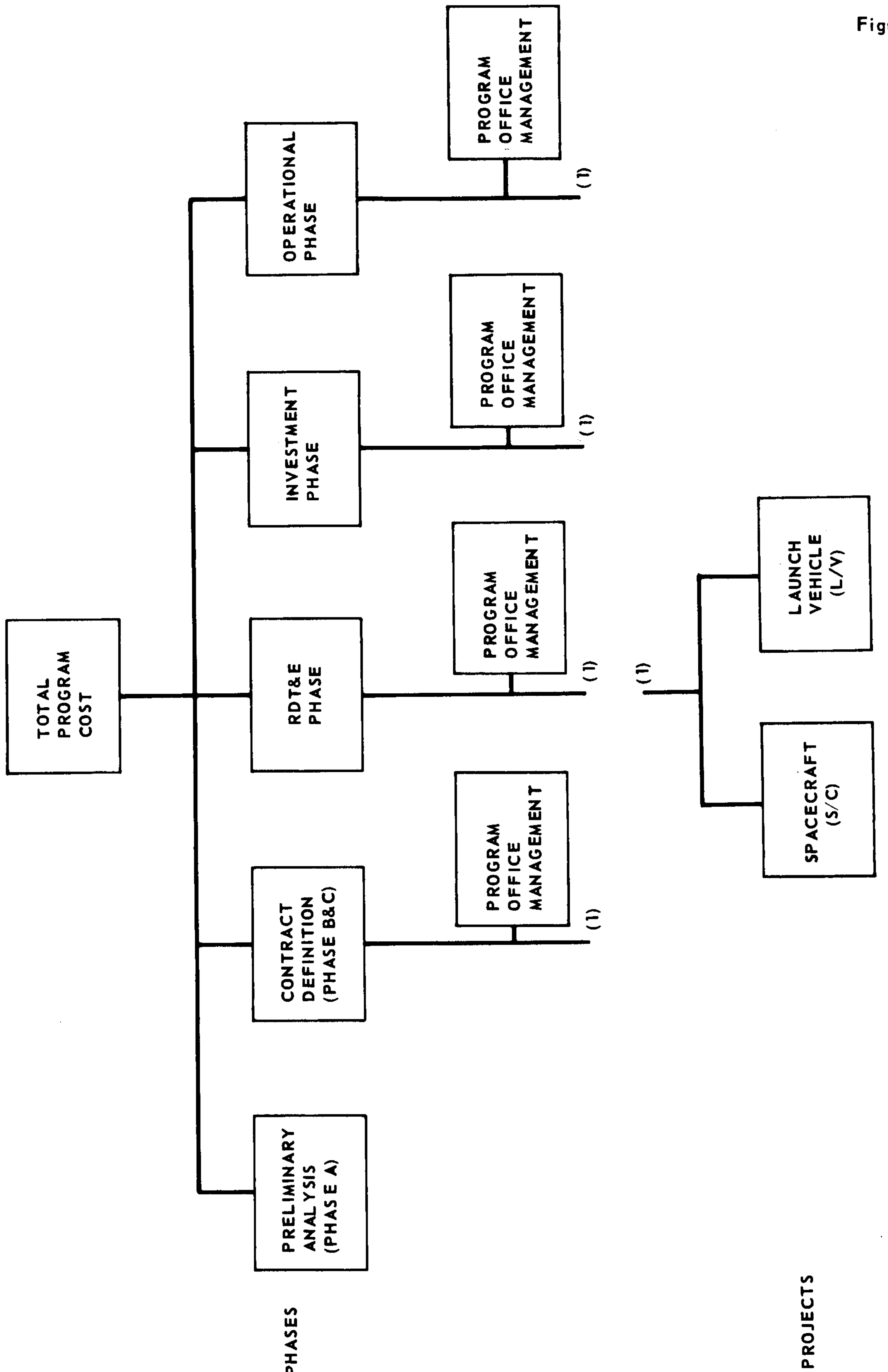
B. Contract Definition - Corresponds to phased project planning, Phases B and C, conducted by several contractors to select a best concept and define preliminary specifications, schedules and plans.

C. Research, Development, Test and Evaluation (RDT&E) - Commences after the completion of Phased Project Planning (PPP) and includes Phase D design, development and test. RDT&E includes all program related costs up to the establishment of an Initial Operational Capability (IOC).

D. Investment - Includes all capital expenditures (including flight systems) required to support the operational phase of the program and corresponds, in part, to the "manufacture" function in PPP Phase D. Funding and activity for this program phase overlaps all or a part of the operational phase.

Figure 5–1

COST ELEMENT STRUCTURE – TOTAL PROGRAM COST



E. Operational - Includes all annually recurring labor and material required to support flight operations from IOC through program completion.

F. Program Office Management - Includes NASA Center Program Office management and system integration activities during the several program phases.

II. Projects:

A. Spacecraft (S/C) - That portion of the flight system which is located above the booster (L/V) separation plane (normally that portion of the flight vehicle injected into orbit).

B. Launch Vehicle (L/V) - Boost stage(s) which provide impulsive velocity required to inject the spacecraft into orbit.

5.1.2 Research, Development, Test and Evaluation Phase (RDT&E) - The RDT&E phase is the design, development, test operations, test hardware, and support effort required for the development and qualification of a system. The RDT&E phase is outlined in Figure 5-2 and discussed in the following paragraphs.

I. Spacecraft Project:

A. Spacecraft (S/C) - That portion of the flight system which is located above the booster separation plane.

B. Project Management and Administration - Project prime contractors cost of managing the project segments.

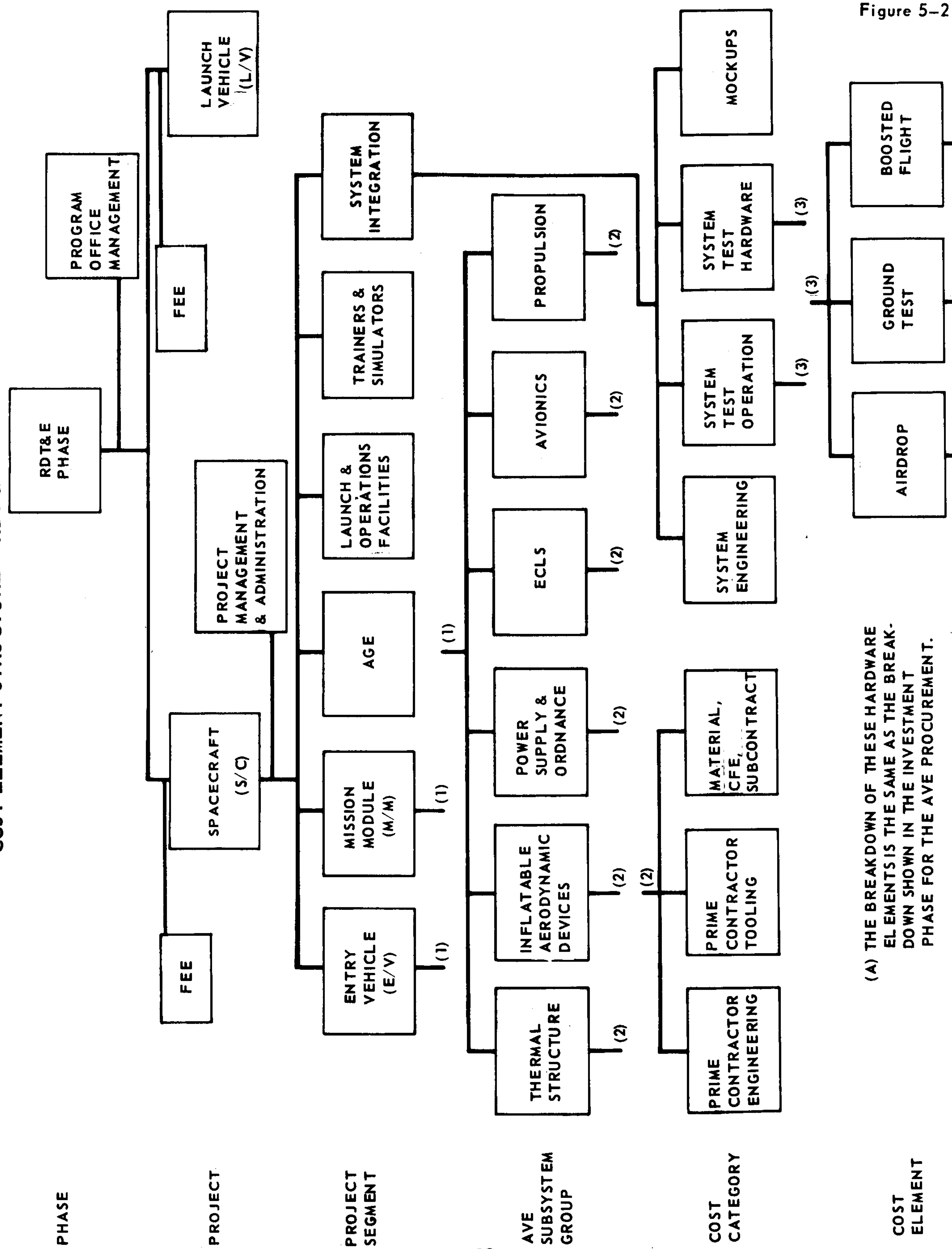
II. Spacecraft Project Segments:

A. Entry Vehicle (E/V) - Design and development of the recoverable portion of the spacecraft.

B. Mission Module (M/M) - Design and development of the expendable cargo and/or propulsion portion of the spacecraft. As a limiting case, it consists of a simple entry vehicle to launch vehicle adapter.

Figure 5-2

COST ELEMENT STRUCTURE – RDT & E PHASE



C. Aerospace Ground Equipment (AGE) - Design, development and fabrication of the AGE required to support the RDT&E phase, includes AGE for handling, transportation, component test, subsystem test, servicing, maintenance and operational equipment, launch and checkout, and refurbishment equipment.

D. Launch and Operational Facilities - Program peculiar buildings and support installations required to support the boosted flight test portion of the RDT&E phase.

E. Trainers and Simulators - Includes the design and fabrication of the necessary training equipment, manuals and instructions.

F. System Integration - Includes system engineering, system test operations, system test hardware, and mockups required for the integration of the several projects segments. In general, it includes those costs which can not be identified by project segment or subsystem excepting the test hardware.

III. Aerospace Vehicle Equipment (AVE) - Subsystem Groups, Design and Development

A. Thermal/Structure Subsystem - Design and development of the basic structural items which includes primary and secondary structure, bulkheads, hatches, doors, docking structure, thrust structure, fixed and movable control surfaces, internal active and/or passive cooling, external thermal protection, equipment mounting structure, landing gear, and launch escape tower. The engineering design and development cost and the initial tooling design and fabrication cost have been defined as follows:

1. Entry Vehicle Crew Section Structure
2. Entry Vehicle Cargo/Propulsion Section Structure
3. Entry Vehicle Ablative Thermal Protection System
4. Landing Gear
5. Launch Escape Tower
6. Mission Module Cargo/Propulsion Section
7. Mission Module Simple Adapter

B. Inflatable Aerodynamic Devices - Design and development of a parachute or sailwing recovery subsystem.

C. Power Supply and Ordnance - Design and development cost of the following subsystems.

1. Electrical Distribution System
2. Fuel Cells
3. Batteries
4. Reactant Supply System (RSS)
5. Hydraulic & Pneumatic
6. Ordnance

D. Environmental Control and Life Support (ECLS) - Includes design and development cost of the Environmental Control System (ECS) for the crew and equipment. Also includes as a separate subsystem, furnishings and equipment, which consists of suits, personal parachutes, food containers, first aid, survival kit and crew accessories.

E. Avionics Subsystems - Design and development cost of the following major subsystems.

1. Guidance and Control
2. Telecommunications
3. Crew Station
4. On-board Checkout

F. Propulsion Subsystems - Design and development cost includes the engines, tanks, and the lines, valves, and miscellaneous items for each of the following subsystems.

1. Entry Attitude Control System (EACS)
2. Vernier Maneuver System
3. Main Orbital Maneuver System
4. Launch Upper Stage System
5. Launch Escape Motors
6. Deorbit Motors
7. Landing Assist Motors

IV. Cost Categories:

A. Prime Contractor Engineering - Design and Development, testing, vendor liaison, and integration as required for each of the subsystems, includes engineering labor only.

B. Prime Contractor Tooling - Initial design and fabrication of the tooling required by the prime contractor, includes tooling labor only.

C. Material, CFE, and Subcontract - Design and development cost of the various subcontractors for each of the subsystems as applicable.

D. System Engineering - Prime contractor engineering and technical activity associated with performing mission analysis, establishing system functional requirements, performing configurational and operational analyses, and establishing design interfaces.

E. System Test Operations - Labor and material required by the prime contractor to conduct the following test operations.

1. Airdrop Test
2. Ground Test
   2.1 Wind Tunnel Test
   2.2 Thermal Qualification Test
   2.3 Propulsion Static Fire Test
3. Boosted Flight Test

F. System Test Hardware - All ground and flight test hardware required by the prime contractor for the development of the system. Costs are segregated by subsystem for each of the following.

1. Airdrop Test Hardware
2. Ground Test Hardware
3. Boosted Flight Test Hardware

G. Mockups - Design and fabrication of development mockups required by the prime contractor.

V. Cost Elements - Prime contractor ground and flight test operations and hardware by type of test as outlined above in paragraphs E and F. The test hardware is segregated by subsystem as outlined in the Investment Phase for AVE procurement.

VI. Launch Vehicle Project:

A. Launch Vehicle - Boost stage(s) which provide impulsive velocity to the spacecraft. The development cost for the launch vehicle is estimated at the project level and includes all costs required to bring a system from a contract definition phase through system qualification. In all cases this includes a five flight vehicle test program in support of the spacecraft boosted flight test program.

5.1.3 Investment Phase - Includes the total hardware procurement cost required for the support of the operational phase. The investment phase is shown in Figure 5-3 and the items not previously defined are outlined below.

I. Project Segments:

A. Additional AGE - Includes labor and material required to fabricate any additional AGE, to that provided in the RDT&E phase, that is required to support the operational phase.

B. Additional Facilities - Any additional facilities, to those provided in the RDT&E phase, that are required to support the operational phase.

II. Cost Items:

A. AVE Procurement - Includes all labor (including sustaining engineering and sustaining tooling) and material required to fabricate, assemble, and test the flight hardware.

B. Initial Spares - Includes the initial quantities of AVE hardware components procured to support the operational phase of the program.

III. Cost Categories:

A. Sustaining Engineering - Project engineering activity in support of AVE fabrication, assembly, and checkout.

B. Sustaining Tooling - All tool engineering, labor and material required to maintain the AVE tooling during production.

C. Production - Manufacturing and quality assurance labor expended by the prime contractor to fabricate, assemble, and checkout the AVE.

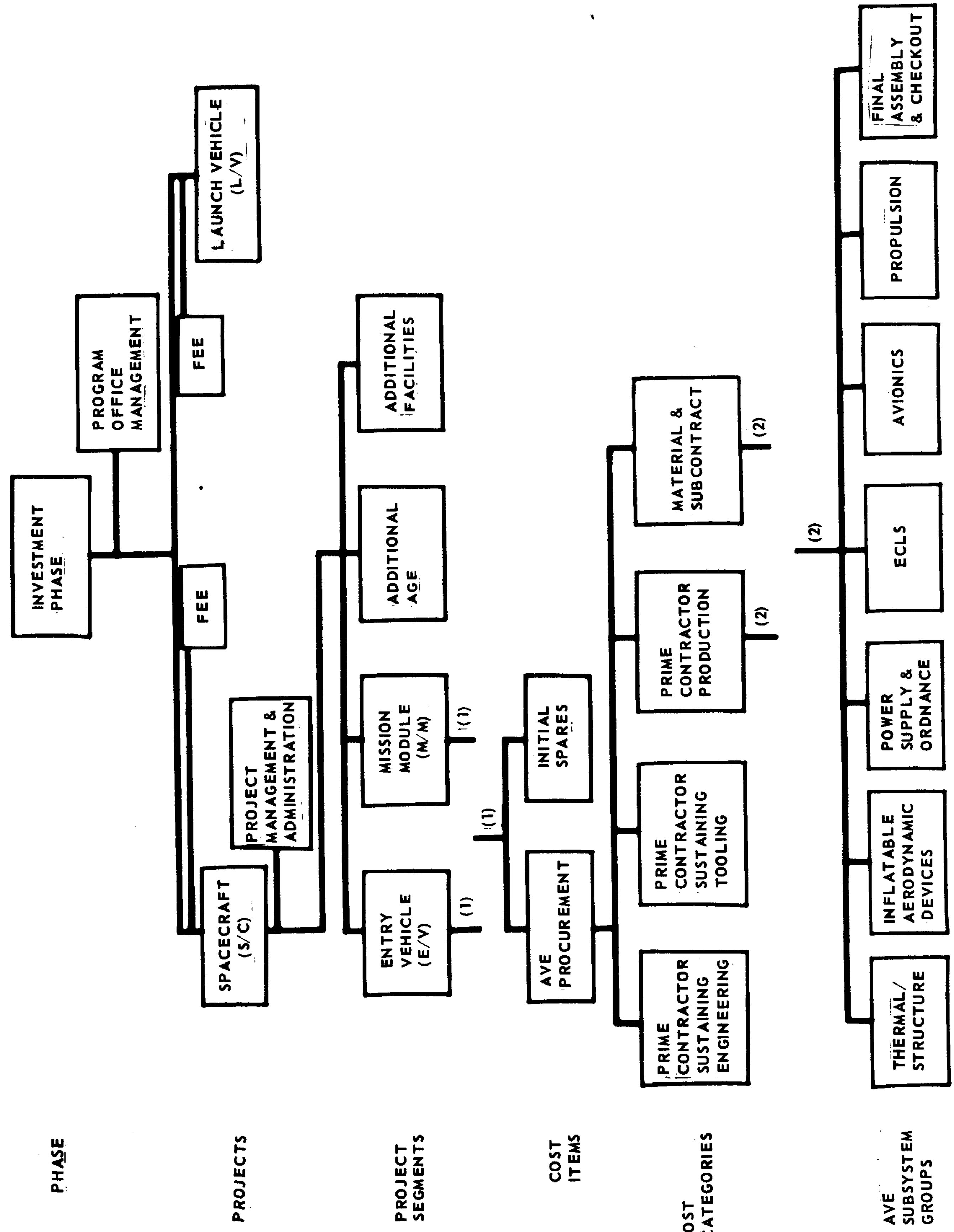
D. Material, Contractor Furnished Equipment (CFE), and Subcontract - Equipment and material procured by the prime contractor for the AVE.

IV. AVE Subsystem Groups

A. Each of the subsystems that make up a group are estimated individually for both production, and material and subcontract.

Figure 5-3

COST ELEMENT STRUCTURE – INVESTMENT PHASE



B. Final assembly and checkout is the final major structural assembly and the acceptance test of the spacecraft.

5.1.4 Operational Phase - Includes the operational costs required for the support of the operational phase as shown in Figure 5-4. The items not previously defined are outlined below.

Cost Item:

A. Mission Support - Includes all labor required to support mission control, tracking and other activities provided in support of flight operations.

B. Launch Operations - Includes all labor and material (other than recurring spares) expended at the launch site to prepare and launch a flight vehicle.

C. Recovery and Abort Rescue - Includes all labor and material expended at the recovery sites and launch site to recover the vehicle or rescue the crew in recovery operations for the manned flight program.

D. Recertification - Includes the labor and materials required to restore a reusable entry vehicle to a flight ready condition including scheduled and unscheduled maintenance, operational spares, and testing. Operational spares include all expendable component on a reusable vehicle which are replaced on a routine basis.

E. Transportation - The total cost (considered a subcontract cost) of transporting the spacecraft components from the manufacturing site to the launch site, and the E/V from recovery site to recertification site to launch site with storage at the recertification site if required

F. Launch Site Support - Includes the sustaining labor and material costs of the launch site such as future planning, repair of government owned equipment, liaison engineering and general office operations.

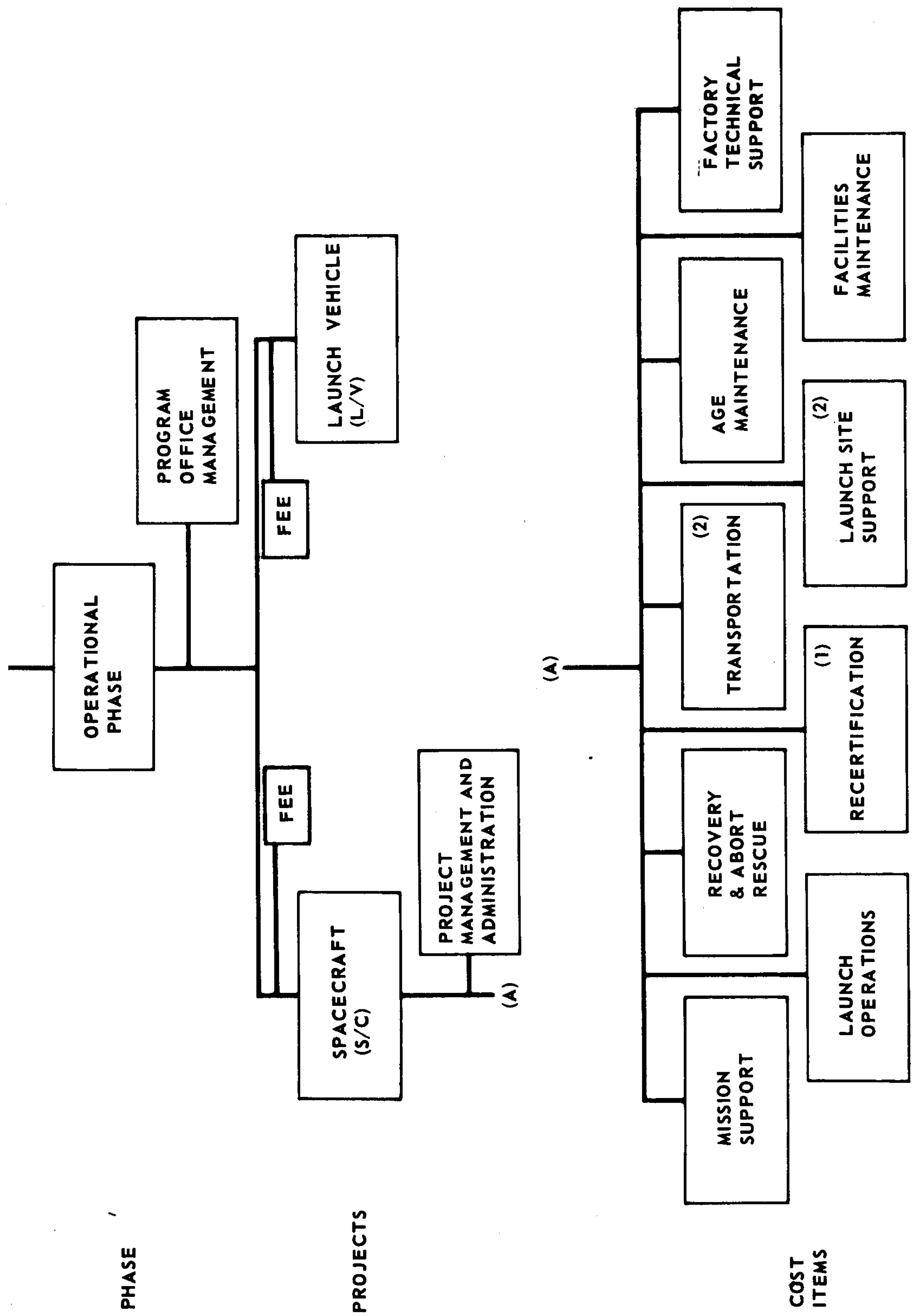
G. AGE Maintenance - Includes labor and material costs required to maintain all operational AGE at the launch site.

H. Facilities Maintenance - Includes labor and material required to maintain the launch facilities in operational readiness.

I. Factory Technical Support - Includes Prime Contractor sustaining engineering and sustaining tooling required to support operational phase.

Figure 5-4

COST ELEMENT STRUCTURE – OPERATIONAL PHASE



(1) ONLY APPLIES IF E/V IS REUSABLE
(2) IDENTIFIED BY E/V AND M/M FOR S/C PROJECT

5.2 Cost Data History and Adjustment - The programs which have provided cost data for this study include Gemini, S-IVB, Mercury, Asset, and some aircraft. However, only the Gemini and S-IVB data have been analyzed in detail.

5.2.1 Gemini Cost Data - A description of the basic Gemini cost data and the necessary adjustments required to organize the data according to the CES are presented in this Section.

5.2.1.1 Gemini Engineerng Cost Data Organization - The Gemini engineering labor expenditures were derived from the corporate cost accounting reports for Job Order 306. Expenditures classified as engineering include:

1. Basic Engineering Division
2. Product Support Division
3. Technical Steno Services
4. Electronic Equipment Division (EED) expenditures that were recorded as engineering manhours; EED expenditures that were recorded as dollars (i.e., no manhours shown in the report) are classified as subcontract
5. Automation Company expenditures
6. Engineering Subcontract Personnel (ESP) manhour expenditures

The accounting reports record expenditures by contract item number, and cost code as outlined in Section 4.1.1.2. The engineering cost data of each subsystem was summarized to shown design, design support, reliability engineering, development testing, mockups, preinstallation acceptance testing (PIA), template tooling, and miscellaneous. The general support and integration items are not identifiable by spacecraft subsystem. These items were summarized only in total (no cost code breakdown) and include mission planning, trainers and simulators, personnel training, thermal qualification test, spacecraft system test (SST), launch support (inplant), publications, spares, Aerospace Ground Equipment (AGE), maintenance of Government Owned Equipment (GOE), and specifications. The ground test item is the only support and integration item that was segregated by cost code to identify structural testing, design, design support, wind tunnel models and testing.

Experiments for the Gemini program were charged to Job Order 383 and are not recorded here.

To derive the data for the OCPDM Study the Gemini engineering expenditures were grouped into three basic categories.

1. Design and Development (non-recurring) - Includes design and development and integration of each subsystem, mission planning, personnel training, structural test portion of ground test, spacecraft systems test procedures and preparation, publications, and specifications for expenditures through June of 1964.
2. Sustaining Engineering (recurring) - Sustaining engineering is the support for the ground and flight test hardware and includes expenditures subsequent to June of 1964 for all items excluding those classified as support.
3. Support Items - Includes trainers, wind tunnel models and testing, thermal qualification test, spares, AGE and mockups.

The data presented in Table 5-1 was derived from the above grouping.

Table 5-1

Adjusted Gemini Engineering Manhours

	Manhours
Design and Development	5,064,882
Sustaining Engineering	2,019,564
Support Items	1,814,318
Total	8,898,764

Design and development engineering has been defined as the cumulative engineering expenditures through June 1964. Expenditures subsequent to this date are considered to be sustaining engineering (recurring). Selection of this date was based on such major milestones as drawing releases, test schedules, and hardware delivery dates. Sustaining engineering for the Gemini program was based on the recorded engineering expenditures at program completion minus the expenditures for design and development and support.

In order to organize the Gemini cost data according to the CES, certain deletions and transfers as outlined in the following paragraphs were necessary.

The target vehicle docking adapter (TVDA) was not included in the design or cost cost analysis and is therefore deleted. The original design configuration of the Gemini entry vehicle included a landing gear and para-glider. Since the development of the items was never completed due to a design configuration change, the costs have been deleted. Spacecraft system test (SST) and preinstallation acceptance test (PIA) expendiutres represent effort required to perform the acceptance tests on all production spacecraft prior to delivery. This function was performed by engineering personnel for the Gemini spacecraft. Since the cost element structure classifies this function to be under the production labor category, the manhours were transferred from engineering labor to production labor and are included with the final assembly and checkout.

St. Louis launch support and maintenance of government owned equipment is included with launch operations (Job Order 356) at Cape Kennedy and Houston. They are, therefore, excluded from the design and development analysis.

Template tooling is designed and fabricated within the engineering division at MDAC-ED. To be compatible with the S-IVB data these expenditures were transferred from the engineering category to the tooling category. Template tooling expenditures are therefore excluded from the engineering design and development analysis.

The design and development cost must be further segregated into program management, system engineering, and subsystem cost. The Gemini cost history does not segregate program management as an item number or cost code. Program management was therefore calculated at about 6% of the total and taken from each of the cost items on a prorated basis.

Cost items that are classified as system engineering include mission planning, personnel training, publications, specifications, and spacecraft system test procedures. Additional functions that are classified as system engineering in the S-IVB data because they were not separable are charged to the appropriate subsystem in the Gemini data. In order to compare the S-IVB and Gemini cost history, the Gemini data was "adjusted" to be compatible with the S-IVB data. Additional system engineering costs for the Gemini program were separated from each of the subsystems cost based on a percentage as derived from the S-IVB data. Segregating program management and system engineering results in the following expenditures for design and development:

	Manhours
Program Management	290,238
System Engineering	1,525,414
Subsystem Design and Development	3,249,230
Total D and D	5,064,882

The subsystem design and development costs are segregated into each subsystem as reported by the item number breakdown. There are certain subsystems that are located in both the entry vehicle and the mission module but the expenditures are recorded by total subsystem. Segregation of these costs between the entry vehicle and the mission module was based on an analysis of the equipment and the relative complexities of installing that equipment in the entry vehicle vs. the mission module.

Program management was separated from the sustaining engineering manhours based on a percentage of the total cost consistent with the design and development cost.

The support items are discussed in the following paragraphs:

Trainers and simulators are segregated as a separate project segment in the CES. A total of 238,265 engineering manhours were expended on the Gemini Program for this item.

Wind tunnel models and testing is included with the ground test portion in the system integration category.

Thermal qualification test is included under the ground test portion in the system integration category.

Spares for the entire Gemini program are included because the spares requirement for five spacecraft vs. twelve spacecraft would not differ significantly. The spares cost is included with program management.

Expenditures for AGE recorded at program completion are 1,026,674 manhours.

Mock-ups are segregated as a separate category in the CES. A total of 54,487 manhours for engineering was expended on the Gemini Program.

Launch support and maintenance GOE are added to the expenditures for launch operations (Job Order 356) at Houston and Cape Kennedy.

A final summary of engineering manhours for the OCPDM study is given in Table 5-2.

Table 5-2

FINAL SUMMARY GEMINI ENGINEERING MANHOURS	
Program Management	502,174
System Engineering	1,525,414
Subsystem Design & Development	3,249,230
Sustaining Engineering	1,903,842
AGE	1,026,674
Trainers & Simulators	238,265
Wind Tunnel & Thermal Qualification Test	398,678
Mock-ups	54,487
Total	8,898,764

5.2.1.2 Gemini Tooling Labor - The tooling division labor manhour expenditures were recorded by contract item number and cost code from the corporate cost accounting reports for Job Order 306. Each item number was summarized to show the tooling division expenditures for tooling, fabrication of mockups, test hardware, and production hardware. Only the expenditures for the tooling function (design, fabrication, and maintenance of the tooling) are considered in the tooling category. The expenditures for mock-ups, test hardware, and production hardware were for fabrication and assembly and, therefore, are transferred to the production labor category.

Expenditures for tooling design, fabrication, and maintenance also appear in the engineering division, the manufacturing division, and the quality assurance division. Since these manhours are also recorded by item number and cost code, the expenditures by these three divisions for tooling have been segregated and transferred to the tooling labor category.

To derive the data for this study, the tooling expenditures were segregated into initial tooling and sustaining tooling. Initial tooling is the design and fabrication of tooling, jigs, and fixtures required for the fabrication and assembly of the spacecraft. Sustaining tooling is the effort required for the maintenance of the production tooling. This segregation was based on hardware delivery dates, tooling division manpower staffing, and an analysis of sustaining tooling as a function of production labor, as indicated by the F-4 aircraft history for carry-on contracts.

Spacecraft number 1, the first structural production article, was delivered in September of 1963. The tooling effort required for the delivery of the first structural production article is considered as the initial tooling cost. The structural article is selected since the tooling is primarily for the structure. The cumulative expenditures for tooling by the four divisions through September of 1963 were 947,663 manhours. Expenditures subsequent to September of 1963 were considered as sustaining tooling.

Table 5-3

Adjusted Gemini Tooling Manhours

	Manhours
Initial Tooling	947,663
Sustaining, 5 Spacecraft	265,441
Sustaining, Ground Test Hardware	56,622
(Total Adjusted Tooling)	1,269,726

5.2.1.3 Gemini Manufacturing and Quality Assurance Labor - The manufacturing and quality assurance labor manhour expenditures were recorded by contract item number and cost code from the corporate cost accounting reports for Job Order 306. Each spacecraft subsystem was summarized to show expenditures for tooling, mock-ups, test hardware, production hardware by lot, and planning and scheduling. The support and integration items were again recorded in total. Manufacturing and quality assurance labor expenditures were recorded separately and then summarized. Expenditures referred to as production labor include both manufacturing and quality assurance.

The expenditures for the production hardware are further separable into lots 1, 2, and 3 and a breakdown by spacecraft number within each lot. Lot 1 consists of Spacecrafts 3A, 1, 2, 3, 4, 5, and 6. Lot 2 consists of Spacecrafts 7, 8, 9, 10, 11, and 12. Lot 3 is adapter 1A, a spare. Each lot segregates the expenditures by spacecraft and a common block of effort that is charged by lot rather than by spacecraft. The common effort accounts for about one-third of the total expenditure in a lot.

Expenditures for Spacecrafts 3A and 1 are recorded in lot 1 with production hardware. These two spacecraft are test hardware; therefore, the expenditures are transferred to the test hardware category and are not included on the learning curve. The analysis of the production expenditures for the 11 production spacecraft resulted in an 85 percent learning curve for the Gemini program. This analysis was performed at the total spacecraft level and not by subsystem. Adapter 1A, lot 3, was transferred to the spares item.

The analysis and organization of the production cost history was consistent with the transfers and deletions that are outlined in the engineering and tooling cost discussions. Table 5-4 presents a summary of the manhours derived.

Table 5-4

Gemini Adjusted Production Manhours	
AGE	1,277,295
Trainers	243,911
Mock-ups	634,614
Spares	172,584
Ground Test Hardware	2,693,782
Flight Test Hardware	3,389,194
Subtotal	8,411,382
Boosted Flight Test (5 Flights) (Launch Operations)	3,732,292
Total	12,143,674

5.2.1.4 Gemini Raw Material, Contractor Furnished Equipment (CFE) and Subcontract - This category includes raw material, castings and forgings, minor subcontract, EED expenditures that were recorded as dollars, minor subcontract, and CFE (major subcontract). Each of the above was recorded separately from the corporate cost accounting reports for Job Order 306. The data was summarized to to show expenditures by subsystem for tooling, mock-ups, test hardware, and production hardware as required by the prime contractor.

Subcontractor costs are not segregated into the various cost elements (i.e., engineering, tooling, production, etc.). The CFE (major subcontractor) costs as reported to MDAC by the various subcontractors did not segregate the cost into design and development and hardware (recurring) costs. The separation of this data into the elements required for the CES was based on a previous analysis. This analysis segregated the subcontractors cost into design and development cost, test hardware required by the prime contractor, and flight hardware required by the prime contractor. With minor exceptions, the remaining categories were used as recorded. Further analysis of the data was consistent with the adjustments that were made in the engineering, tooling, and production areas. The first unit cost was computed by using a 90 percent learning curve for all of the procured materials and hardware, except the RCS and OAMS engines where a 95 percent learning curve was used.

The support areas, mission planning, trainers, ground test, thermal qualification, SST, launch support, publications, spares, AGE, maintenance of GOE, specifications, and mock-ups, were all recorded and analyzed consistent with the analysis and adjustments that are outlined in the engineering, tooling, and production areas.

Table 5-5 outlines the cost as derived for the OCPDM study.

Table 5-5

Gemini Adjusted Material, CFE, Subcontract Cost

	Thousands Dollars (1969)
Design and Development	$246,096
AGE	71,833
Trainers	19,892
Mock-ups	673
Spares (Total Program)	21,948
Ground Test Hardware	44,486
Flight Test Hardware (5 S/C)	48,830
Subtotal	$453,758
Boosted Flight Test (5 Flights) (Launch Operation)	2,967
Total	$456,725

5.2.1.5 Launch Operations and Launch Support - The launch operations and launch support costs for the Gemini five flight development program were determined from the data and equations presented in Book 2 of Vol. II. The development portion of the Gemini program required 3,732,292 manhours and $2,967,000 in material and subcontract costs.

The organization, adjustment and analyses of the data is discussed in Book 2. The resulting adjusted data were used to develop the CER's. Included in these totals are launch operations, launch support, mission control support, AGE maintenance, facilities maintenance, launch site peculiar AGE, and facilities activation. These are the activities encompassed by the Gemini launch operations contract with the additions or transfers discussed in previous paragraphs. The data is representative of the activities and expenditures actually associated with the launch activities of the five Gemini flights assumed to be representative of the development program.

5.2.1.6 Gemini Cost History - The Gemini cost history has been organized into the cost element structure (CES) and is presented in Table 5-6. The adjustments required to organize the Gemini cost history to the CES were discussed in paragraphs 5.2.1.1. through 5.2.1.5. The recorded data are consistent with the ground rules outlined in Section 3.

The following labor rates and economic adjustments were applied to the Gemini data:

	Inplant	Remote Site
Engineering	$20.00/MH	-
Tooling	$13.40/MH	-
Production	$11.80/MH	$16.00/MH

Material, CFE and subcontract dollars have been escalated at 5% per year for 5-1/2 years. All costs exclude fee.

The following cumulative average learning curves were used for the Gemini data:

Sustaining Engineering	70%
Sustaining Tooling	77%
Production (1)	85%
Material, CFE, Subcontract (2)	90%

NOTES: (1) Applied to all subsystems except the mission module structure where a 90% curve was used.

(2) Applied to all subsystems except the EACS and VMS engines where a 95% curve was used.

Definitions of the specific cost elements are given below and are numbered and titled in accordance with the data presented in Table 5-6.

1.0 (A) Project Management and Administration - Includes the basic tasks of program definition, program management and system development, management of the spare parts supply program, all effort associated with producing, submitting and maintaining documentation for customer required contract data, and miscellaneous engineering effort that is not directly related to the design and development of hardware or other specific RDT&E tasks.

1.1 Entry Vehicle (E/V) - Design and development.

1.1.1 Thermal/Structure - Includes all basic structure, hatches, shingles, insulation, ablative heat shield, and equipment mounting structure.

1.1.2 Inflatable Aero Devices - Includes the recovery parachute system.

1.1.3 Power Supply and Ordnance - Includes the electrical power distribution system, electrical circuitry and batteries, and ordnance.

1.1.4 Environmental Control, Life Support - Includes all the ECS equipment that is located in the E/V, the ejection seats, and personal equipment.

1.1.5 Avionics - Includes guidance and control, communications, instrumentation, crew station, rendezvous radar, telemetry, and recovery aids.

1.1.6 Propulsion - Includes the entry attitude control system.

1.2 Mission Module (M/M) - Design and development.

1.2.1 Thermal/Structure - Includes the basic structure, thermal protection, and equipment mounting structure.

1.2.2 Power Supply and Ordnance - Includes the electrical distribution system, electrical circuitry, fuel cells, the reactant supply system,

Table 5-6
GEMINI COST SUMMARY
(ALL FIGURES IN THOUSANDS)

		PRIME CONTRACTOR LABOR MANHOURS				1969 DOLLAR COST				
		ENGR.	TOOL	PROD	TOTAL	ENGR.	TOOL	PROD	MAT CFE, SUBCON	TOTAL
1.0	SPACECRAFT (S/C)									810,685
1.0A	PROJECT MANAGEMENT & ADMINISTRATION	502			502	10,040			600	10,640
1.1	ENTRY VEHICLE (E/V) (DESIGN AND DEVELOPMENT)	2,452	806		3,258	49,040	10,796		153,933	213,769
1.1.1	THERMAL STRUCTURE	848	806		1,654	16,960	10,796		4,540	32,296
1.1.2	INFLATABLE AERO DEVICES	97			97	1,940			8,735	10,675
1.1.3	POWER SUPPLY & ORDNANCE	344			344	6,880			2,357	9,237
1.1.4	ENVIRONMENTAL CONTROL & LIFE SUPPORT	293			293	5,860			23,975	29,835
1.1.5	AVIONICS	786			786	15,720			87,307	103,027
1.1.6	PROPULSION	84			84	1,680			27,019	28,699
1.2	MISSION MODULE (M/M) (DESIGN & DEVELOPMENT)	798	142		940	15,960	1,902		90,761	108,623
1.2.1	THERMAL/STRUCTURE	256	142		398	5 120	1,902		557	7,579
1.2.2	POWER SUPPLY & ORDNANCE	227			227	4,540			41,502	46,042
1.2.3	ENVIRONMENTAL CONTROL & LIFE SUPPORT	105			105	2,100			6,893	8,993
1.2.4	AVIONICS	91			91	1,820			1,591	3,411
1.2.5	PROPULSION	119			119	2,380			40,218	42,598
1.3	AEROSPACE GROUND EQUIPMENT (AGE)	1,027		1,277	2,304	20,540		15,072	71,833	107,445
1.4	TRAINERS & SIMULATORS	238		244	482	4,760		2,878	19,892	27,530
1.5	SYSTEM INTEGRATION									342,678
1.5.1	SYSTEM ENGINEERING									(31,302)
1.5.2	SYSTEM TEST OPERATIONS									(70,659)
1.5.2.1	GROUND TEST									
										7,980
1.5.2.2	BOOSTED FLIGHT TEST (5 FLIGHTS)									62,679
1.5.3	SYSTEM TEST HARDWARE									(231,476)
1.5.3.1	GROUND TEST HARDWARE (S/C)									89,032
1.5.3.2	BOOSTED FLIGHT TEST HARDWARE (5 S/C)									142,444
1.5.3.2.1	AVE PROCUREMENT (5 E/V) & SPARES									105,366
	SUSTAINING ENGINEERING									19,680
	SUSTAINING TOOLING									3,896
	PRODUCTION, MATERIAL, CFE, SUBC.									64,941
	SPARES									
1.5.3.2.2	AVE PROCUREMENT (5 M/M) & SPARES									16,849
	SUSTAINING ENGINEERING									37,078
	SUSTAINING TOOLING									6,667
	PRODUCTION MATERIAL, CFE, SUBC.									781
										22,494
	SPARES									7,136
1.5.4	MOCKUPS	(54)		(635)	(689)	(1,080)		(7,488)	(673)	(9,241)

and ordnance.

1.2.3 Environmental Control System - Includes all ECS equipment that is located in the mission module.

1.2.4 Avionics - Includes communications and instrumentation equipment only.

1.2.5 Propulsion - Includes the orbit attitude control system and the retrograde system.

1.3 Aerospace Ground Equipment (AGE) - Includes the design, development, procurement, and fabrication of all the AGE for the Gemini Program.

1.4 Trainers & Simulators - Includes the design and fabrication of all trainers and simulators.

1.5 System Integration - The system integration costs include system engineering and the ground and flight test operations and hardware required to bring the system to operational status.

1.5.1 System Engineering - Includes mission planning, publications, and specifications as separable cost elements on the Gemini program. Additional cost elements were derived using the S-IVB data as a base. The major item in this cost category is engineering system design which includes total system non-separable hardware design effort, materials research and production methods support, configuration management, first article inspection and reliability plan implementation. It also includes the preparation and implementation of inplant training courses.

1.5.2 System Test Operations

1.5.2.1 Ground Test Operations - Includes wind tunnel models and testing and spacecraft thermal qualification testing.

1.5.2.2 Boosted Flight Operations - Includes support costs from St. Louis, Houston, and Cape Kennedy for the launching of 5 spacecrafts.

1.5.3 System Test Hardware

1.5.3.1 Ground Test Hardware - Includes all major and minor test hardware required for the development test program. Includes boiler-plates, static test vehicles, compatibility test unit, electronic systems test unit, thermal qualification test vehicle, and all miscellaneous test parts.

1.5.3.2 Boosted Flight Hardware - Includes five (5) complete spacecrafts for the flight test program as defined in the study ground rules for the RDT&E phase.

1.5.4 Mockups - Includes the design and fabrication of all mockups for the Gemini program.

5.2.2 Saturn S-IVB Stage - The Saturn S-IVB stage (Saturn V configuration) historical cost data were analyzed and organized into the cost element structure as defined in Section 5.1 in accordance with the groundrules and assumptions given in Section 3. The methodology and data sources employed in generating these data are defined in the following paragraphs.

Since the S-IVB accounting system does not segregate costs by program phase, it was necessary to establish a cut-off date in relation to scheduled activity to identify costs associated with the RDT&E phase. The date selected, delivery of the fifth test stage from Sacramento (7/27/66), seemed to best define the S-IVB RDT&E phase when used in conjunction with data from the Gemini program. It is recognized that total effort through a specific date does not precisely define an RDT&E phase but in this case it was assumed that any RDT&E effort continuing after the selected date would be offset by scope changes or investment phase work-in-process prior to that date.

5.2.2.1 Saturn S-IVB Cost Data Organization - The primary source of S-IVB cost data used in this study was the Work Outline Retrieval (WOR) cost report of cumulative Saturn costs through July 31, 1966. Since this report does not segregate initial design and tooling effort from sustaining effort, it was necessary to compute initial engineering design and tooling (AVE design and development test) to determine costs applicable to the RDT&E phase. In the case of engineering design, it was assumed that the WOR report of total engineering hours through 7/31/66 represented an undetermined number of equivalent units completed through that date. A detailed S-IVB cost study completed in 1965 provided the basis for estimating engineering hours per unit for individual flight stages. A summation of these estimated hours for stages 501 through 507 (the first seven Saturn S-IVB/V units) resulted in a total estimate only 2/10 of 1% greater than the reported hours through 7/31/66. It was therefore concluded that these reported hours from the WOR report through 7/31/66 represented the completion of seven equivalent units. Fitting a learning curve to the estimated hours for these seven units resulted in a 65% slope and a theoretical first unit (T_1) which is used in the equation to estimate sustaining engineering for the boosted flight test hardware. This T_1 is considered to be part of total initial (RDT&E) engineering, and the values for subsequent units on the learning curves are computed to obtain sustaining engineering. To account for common effort applicable to concurrent production of the Saturn S-IVB/IB configuration, the computed values for sustaining engineering applicable to units 2 through 7 have been determined based on shifted schedule positions. Thus the curve values applied for Saturn S-IVB/V units 2 through 7 are those for units 3, 6, 8, 11, 13 and 15. The sum of computed engineering hours for units 2 through 7 at the above noted curve positions represents sustaining engineering included in the WOR report total engineering hours through 7/31/66. Initial (RDT&E) engineering design was then computed as the difference between total reported hours through 7/31/66 and the computed sustaining hours for units 2 through 7. A similar method was employed to compute initial tooling and sustaining tooling. A 57% learning curve was used for the sustaining tooling first unit cost.

Stage engineering, lab testing and tooling costs not separable into the defined subsystems were accounted for in a subsystem common reporting category in the WOR cost report. This category includes subsystem installations, final systems and subsystems checkout and other total stage tasks not identified with a particular subsystem. These reported subsystem common costs were allocated to the four stage subsystem categories in proportion to the basic separable costs reported for these categories.

5.2.2.2 Saturn S-IVB Cost History - The S-IVB cost data have been organized into the CES and are presented in Table 5-7. Definitions of the specific cost elements are given below and are numbered and titled in accordance with the data presented in Table 5-7.

Table 5–7
S-IVB COST SUMMARY
(ALL FIGURES IN THOUSANDS)

		PRIME CONTRACTOR LABOR MANHOURS						1969 DOLLAR COST						
		ENGINEERING						ENGINEERING						
		DESIGN	TEST	SUB TOTAL	TOOL	PROD	TOTAL	DESIGN	TEST	SUB TOTAL	TOOL	PROD	MAT'L, CFE, SUBCON	TOTAL
1.0	SPACECRAFT (S/C)													568,446
1.0(A)	PROJECT MANAGEMENT & ADMINISTRATION	848	31	879	3	154	1,036	16,960	620	17,580	40	1,817	840	20,277
1.1	MISSION MODULE (M M) (DESIGN AND DEVELOPMENT)	1,889	3,908	5,797	1,485		7,282	37,780	78,160	115,940	19,899		5,202	141,041
1.1.1	THERMAL STRUCTURE	380	1256	1636	1328		2964	7600	25,120	32,720	17,795		3,185	53,700
1.1.2	POWER SUPPLY & ORDNANCE	275	557	832			832	5,500	11,140	16,540			257	16,897
1.1.3	AVIONICS	385	608	993	40		1033	7,700	11,960	19,860	536		460	20,856
1.1.4	PROPULSION	849	1,487	2,336	117		2,453	16,980	29,740	46,720	1,568		1,300	49,588
1.2	AEROSPACE GROUND EQUIPMENT (AGE)	2,623	714	3,337	489	4,976	8,811	52,460	14,280	66,740	6,673	58,717	32,002	164,132
1.3	SYSTEM INTEGRATION													242,996
1.3.1	SYSTEM ENGINEERING													64,593
1.3.2	SYSTEM TEST OPERATIONS													48,570
1.3.2.1	GROUND TEST OPERATIONS													26,152
1.3.2.2	BOOSTED FLIGHT TEST OPERATIONS(5 FLT)													22,418
1.3.3	SYSTEM TEST HARDWARE													125,595
1.3.3.1	GROUND TEST HARDWARE													61,542
1.3.3.2	BOOSTED FLIGHT TEST HARDWARE (5 VEH)													
	AVE PROCUREMENT (M/M) SPARES													64,053
	SUSTAINING ENGINEERING													15,200
	SUSTAINING TOOLING													4,208
	PRODUCTION, MAT'L, CFE, SUBC'													41,034
	SPARES													3,611
1.3.4	MOCKUPS	50	149	199		5	204	1,000	2,980	3,980		59	198	4,237

1.0 (A) Project Management and Administration - This element includes the basic tasks of program definition, program management and system development as well as the management of the spare parts supply program, program coordination for all logistics support activities, all effort associated with producing, submitting and maintaining documentation for customer required contract data, and miscellaneous engineering effort that is not directly related to the design and development of hardware or other specific RDT&E tasks.

1.1 Mission Module Design and Development

1.1.1 Thermal/Structure - Includes tank structure, thrust structure, forward skirt, aft interstage and aft skirt.

1.1.2 Power Supply - Includes silver-zinc batteries, static inverter/converter, electrical distribution system, grounding system and wire harness assemblies.

1.1.3 Avionics - Includes the main engine closed-loop hydraulic power system for powered flight control and the stage instrumentation or data acquisition system which includes measurement pickup transducers, signal conditioners, multiplexers, transmitters and antennas.

1.1.4 Propulsion - Includes the propellant utilization system, the main engine chilldown system, propellant tank pressurization, pneumatic control systems, the auxiliary propulsion system (APS), and the stage separation ullage rockets and retro rockets.

1.2 AGE - The AGE costs are segregated into the two general categories of Ground Support Equipment (GSE) and Non-Deliverable Support Equipment (NDSE). GSE is categorized by major function and includes the design, test and production of all items of GSE required at inplant and field station locations. NDSE includes test equipment utilized in the contractor's plant until completion of the contract, and special field station equipment related to test structures and buildups.

1.3 System Integration - The system integration costs include system engineering and the ground and flight test operations and hardware required to bring the system to operational status.

1.3.1 System Engineering - The system engineering activities include, within the general category of logistics support, the development and preparation of technical support documents and manuals, the determination of maintenance support requirements and the necessary maintenance documentation, and the preparation and implementation of inplant training courses. Also included is technical liaison and test support at the Marshall Space Flight Center. The major item in this cost category is engineering system design which includes total system non-separable hardware design effort, materials research and production methods support, configuration management, first article inspection, and reliability plan implementation. Also included is system production which includes non-separable production support, tool engineering research and development and fabrication training courses.

1.3.2 System Test Operations

1.3.2.1 Ground Test Operations - Ground test operations included the wind tunnel testing and the propulsion static test activities. The propulsion static test activities include the activities involved in site operations and ground test program at the Sacramento test center as well as inplant support at Huntington Beach. Site operations includes the planning effort for all stage testing at the test center and the manufacturing effort for maintenance of government furnished facility and equipment items. The ground test program includes all effort at the test center to plan, conduct and analyze tests on the Battleship stage, Facilities Checkout stage and stage acceptance firing on flight stages. The 7/31/66 cut-off date selected for defining the RDT&E phase covers the period of Battleship testing from April, 1964 to December, 1964; the Facilities Checkout stage testing from February, 1965 to June, 1965; and acceptance firing of the first Saturn S-IVB/V flight stage from March, 1966 to July, 1966. Acceptance firing of four Saturn S-IVB/V stages occurred during the above described time period but the costs for this effort have been deleted to account for Saturn S-IVB/V costs only in accordance with the study ground rules. The above described Sacramento testing was conducted on a two stand complex with a common control center.

1.3.2.2 Boosted Flight Test Operations - A great deal of the S-IVB flight test activity at the Florida Test Center was common to the IB and V configurations and four IB vehicles were launched prior to the first Saturn V launch, the total cost of combined IB and V activity has been included in this category to account for all S-IVB test support. It includes program management and support activities, installation, checkout and maintenance of GSE, and stage operations activities. The major subcategory of stage operations includes verification of procedures, equipment and facilities through use of the Facilities Checkout stage, engineering verification of checkout procedures, checkout and launch operations activities and post launch operations. All of these activities took place at complex 34 and 37 for IB lunches and on the 2 Pad Complex 39 for V launches. Activity began at the test center in January, 1965 with Pad 34/37 occupancy for facilities checkout and continued with the first four Saturn IB launches on 2/26/66, 7/5/66 and 1/22/68 and the first two Saturn V launches on 11/9/67 and 4/4/68.

1.3.3 System Test Hardware

1.3.3.1 Ground Test Hardware - The ground test units include all stage test hardware utilized in the inplant and Sacramento ground test operations (excluding flight test stage static fired at Sacramento) as well as special test stages delivered to NASA for testing at Government facilities. This test hardware consists of qualification test parts used in miscellaneous system testing and a number of partial stages used at various locations for development testing. The stages retained for contractor testing include the hydrostatic, battleship, structures (diverted from cancelled all systems stage), and the engineering development fixture. The stages delivered to NASA for special customer testing include the dynamics, facilities checkout and 500 ST stage simulator.

The total labor and material costs for ground test hardware procurement represent a combination of actual reported costs and computed costs. Sustaining engineering is not normally charged to ground test hardware; however, the task plan assigned a specific matrix number to the 500 ST stage simulator and the design hours reported in the WOR cost report against this matrix were included as sustaining engineering under ground test AVE procurement. Sustaining tooling, not reported separately in the WOR report, was assumed to be one equivalent flight unit for all ground test hardware. The computed value of the second unit on the above described tooling learning curve was allocated to sustaining tooling for ground test procurement. Actual production labor hours and material and subcontract dollars for ground test hardware were identified in the WOR cost report for the 500 ST stage and the engineering development fixture only. Production costs for the remainder of the test stages (hydrostatic, battleship, structures, dynamics and facilities checkout) were computed from detailed manufacturing labor and material estimates by stage which were incorporated in the 1965 S-IVB cost study. The total production labor and material costs for all ground test hardware as computed in this analysis closely approximates the total production cost for the first three units that would be obtained from application of the production and material and subcontractor equations.

1.3.3.2 Boosted Flight Test Hardware - Flight test hardware procurement includes five complete stages for the test program as defined in the study groundrules for the RDT&E phase. Since the WOR cost report used as the primary data source in this study does not identify S-IVB AVE hardware costs by individual stage, it was necessary to compute all of the costs allocated to the five stages included in flight test hardware procurement. The sustaining engineering and tooling costs have been obtained from the same learning curve analysis utilized in computing initial engineering design and tooling. As noted above, all of the first unit (T_1) costs have been included in initial engineering and tooling, and sustaining costs applicable to the remaining four units have been computed at curve values 3, 6, 8 and 11. The 1965 S-IVB cost study provided the basis for estimating production labor hours and material and subcontract dollars per unit for individual flight stages. Application of learning curves to these stage estimates resulted in computed theoretical first unit (T_1) costs for production labor and material and subcontracts, with learning curve slopes of 90% and 95% respectively. The computed production and material and subcontract costs applicable to the five flight test stages have been determined in relation to schedule position which displace for ground test hardware as noted above and for common effort applicable to concurrent production of the Saturn IB configuration. As a result, the curve values applied to the five Saturn V flight test stages are those for units 4, 6, 7, 9 and 10. The distribution of these computed costs by stage subsystem was based on ratios obtained from the 1965 S-IVB cost study.

1.3.4 Mockups - The cost of mockups shown in Table 5-7 includes all effort for the design and fabrication of AVE and AGE mockups, the design, fabrication and wind tunnel testing of scale models, and the fabrication of all required display models.

5.2.3 Mercury Cost Data - The Mercury cost history as currently summarized does not match the cost element structure. Available time and manpower precluded the analysis and organization of the Mercury data into the cost element structure. For this reason, only a limited amount of data from the Mercury program was usable. This data is indicated in the discussion of the CER when it is used.

5.2.4 ASSET Cost Data - The only available ASSET data that was considered usable was the engineering structural design cost. This data is given in the CER discussion.

5.2.5 F-4 Aircraft - F-4 data as available and applicable was used. This data is given in the discussion of the CER when it is used.

5.2.6 Vendor Supplied Cost Data - See Volume II, Book 4 for the cost data supplied by vendors for this study.

6. SPACECRAFT COST ESTIMATING RELATIONSHIPS - All of the Spacecraft Cost Estimating Relationships (CER's) that have been developed for the OCPDM study are discussed in this section. The order of presentation attempts to follow the cost element structure as outlined in Section 5. However, the first unit cost CER's are presented first since their results are used extensively throughout the RDT&E, Investment and Operational phases. The cost element structure divides, as major projects, the spacecraft and the launch vehicle. The spacecraft CER's are presented here and the launch vehicle CER's in Section 7. See Appendix C for a complete list of the CER's and Appendix D for symbol definitions.

6.1 First Unit Cost CER's - The first unit cost CER's for the spacecraft are divided by project segment into the entry vehicle and mission module and are then further separated into each subsystem as applicable to each project segment. The cost categories involved for the spacecraft are:

1. Sustaining Engineering
2. Sustaining Tooling
3. Production
4. Material, Contractor Furnished Equipment (CFE), and Subcontract

The first unit cost as used in this study is the theoretical cost of the first production flight article. It is referred to as theoretical rather than actual because it is determined by extrapolating back to unit number one from the cost history of several production units. The first unit cost is for production flight articles only and is considered to be unaffected by the quantity of ground test hardware that is produced. CER's for the prime contractors labor cost are presented in Sections 6.1.1 through 6.1.3 and the material, CFE, and subcontract cost are presented in Section 6.1.4.

6.1.1 Sustaining Engineering - Sustaining engineering is the prime contractor's project engineering activity required to support the fabrication, assembly, and checkout of hardware. Sustaining engineering is difficult to identify by subsystem and is therefore estimated at the project segment level.

The CER for sustaining engineering has been derived as a function of the prime contractor's engineering design and development cost. Since this cost will vary directly with the size, definition, and complexity of the vehicle, the sustaining engineering cost will reflect a cost compatible with the vehicle being produced. Because the size range of the vehicles to be estimated is so large, the sustaining engineering CER has been written in two parts. One part is a function of the structural costs and the other a function of the remaining subsystems. Cost history from the Gemini program indicates that the sustaining engineering required for the non-structural subsystems is considerably more than the structure. The Gemini and S-IVB programs provide the only data available for this CER. However, each data point was arrived at by using different learning curves (70% on Gemini, 65% on S-IVB), and additionally the S-IVB data include some ground test hardware on the learning curve. Therefore the data points are incompatible and cannot be compared. The CER is based on the Gemini data since this program represents the type of vehicle to be estimated. (Manned earth orbit entry vehicle.)

$$CSEE = .64 \left[\frac{CESRE}{KENGR}\right]^{.848} (KENGR) + .23 \, (CESSRE)$$

where

CSEE = First unit sustaining engineering cost, E/V.

CESRE = Prime contractor engineering structural design and development dollar cost (includes the thermal/structural group and the propellant tanks from the upper stage launch propulsion system), E/V.

CESSRE = Prime contractor engineering dollar cost of the non-structural subsystems, E/V.

KENGR = Labor rate and escalation factor for engineering.

The above CER is also used for the mission module. See Appendix C for the CER and Appendix D for the symbol definition.

6.1.2 Sustaining Tooling - Sustaining tooling is the prime contractor's tooling labor and material expenditure required for the maintenance of the production tooling. Tooling used to build the vehicle must be replaced, repaired, and realigned during the production cycle. Available cost data for tooling includes the prime contractors labor, procured materials, and subcontracted effort. Since the amount of subcontracted effort varies from program to program, the only method of analyzing tooling cost was to add all of the cost categories (prime contractor labor, material, and subcontract) together. Available manpower and time were insufficient to perform a detail analysis of the cost history to separate the material and subcontract costs. Current experience indicates that the material required to support the sustaining tooling effort is $1.00 per tooling manhour that is expended. This experience is applied to the cost history in order to separate the total expenditures into labor and material. The resulting costs are then used for the development of the CER's. The CER for sustaining tooling has been derived as a percentage of the hardware production cost (prime contractor production labor). Sustaining tooling is based on the prime contractor production effort only since the tool maintenance is associated with those items that are fabricated and assembled by the prime contractor. Since the production cost will vary directly with size, definition, and complexity of the vehicle, the sustaining tooling cost will be compatible with the vehicle being produced.

Both Gemini and F-4 sustaining tooling costs for first unit are 16 percent of the production labor manhours excluding final assembly and checkout. Final assembly and checkout manhours are excluded because it is a relatively high cost area for spacecraft and is primarily associated with the complex subsystems that are in the spacecraft. The S-IVB sustaining tooling is 272% of production manhours. This high percentage is due to the steep learning curve applied to the S-IVB data (57% curve vs. a 77% curve used on Gemini and the F-4) and the fact that ground test hardware is included on the learning curve. The data are therefore not comparable to the Gemini or F-4 data. While the S-IVB data show a higher ratio for first unit cost, at some low quantity, the ratio will be lower than the F-4 or Gemini data because of the steeper learning curve applied to the S-IVB data. The 57% learning curve presents the undesirable effect of a very low cost for higher quantities and therefore would require a change in the learning curve at some quantity to maintain a reasonable level of tooling support. The CER is influenced considerably by the F-4 data since it presented the greatest amount of confidence because of the large quantity base for the data.

$$CSTE = .16 \left(\frac{CPE}{KPROD}\right) KTOOL$$

where

CSTE = First unit sustaining tooling cost, E/V.

CPE = Prime contractor production labor cost excluding final assembly and checkout (excludes material, CFE, and subcontract costs).

KPROD = Production labor rate.

KTOOL = Tooling labor rate.

The above CER is also used for the mission module. See Appendix C.

6.1.3 Production - Production labor includes the prime contractor's manufacturing and quality assurance labor. The cost history available for the production cost category includes Gemini, F-4 aircraft, S-IVB, and Mercury data. The range of subsystems to be estimated for the OCPDM study is more extensive than the subsystems represented by any one of the listed vehicles. The quantity of data is therefore very limited for any one subsystem and in many cases only one data point is applicable. For this reason the production cost has been assumed to be a function of the weight of each subsystem. The F-4 aircraft data present the best breakdown of the cost data and because of the large quantity produced, it presents the data with the most confidence. However, the number of subsystems that are applicable to spacecraft are limited. The F-4 data used in this analysis, however, does indicate a very reasonable amount of correlation with the spacecraft data. The Gemini subsystem production costs are based on a detailed analysis of production work orders. This analysis segregates the cost into entry vehicle structure, mission structure, and total subsystem installations by entry vehicle and mission module. The subsystem installation cost was further segregated by subsystem for the OCPDM study. This was done on a relative complexity basis for each of the subsystems.

The S-IVB data is the result of an extensive analysis performed by the Advanced Systems Cost Analysis Group of MDAC-ED.

The CER's for all subsystems other than structure are based on the cost history of each subsystem as applicable with weight as the estimating parameter. Subsystems for which there is no cost history were estimated from existing data on a similarity and relative complexity basis.

6.1.3.1 Structure Subsystem - A detailed discussion of the structure subsystem is given because it represents one of the high cost areas. The structural subsystem includes the basic structure, bulkheads, hatches, doors, windows, docking structure, thrust structure, aerodynamic surfaces, and all equipment mounting structure. The data available for the analysis of the structural fabrication and assembly costs includes the Gemini entry vehicle and adapter, Mercury entry vehicle and adapter, Saturn S-IVB, and the F-4 aircraft.

The cost categories that make up the structural cost include the prime contractor's labor, procured materials, and subcontracted effort. The fabrication of structure is primarily done by the prime contractor with only overload and miscellaneous items subcontracted. Since the amount of subcontract varies from program to program, the only method of analyzing the cost data was to add all of the cost categories together. Available manpower and time were insufficient to perform a detailed analysis of the cost history to separate the material and subcontract costs in order to put all of the programs on a comparable basis. Therefore, the basic CER's that were developed include labor, material, and subcontract.

Due to the configurations of the vehicles represented by the historical programs and the large variations in the configurations to be estimated, the structural subsystem has been separated into 6 sections as follows:

1. Entry Vehicle - Crew Section
2. Entry Vehicle - Cargo/Propulsion Section
3. Entry Vehicle - Aerodynamic Surfaces
4. Entry Vehicle - Thermal Protection System
5. Mission Module - Simple Adapter
6. Mission Module - Cargo/Propulsion Section

The entry vehicle crew section houses the crew and most of the mission equipment. The entry vehicle cargo/propulsion section exists only for an integral configuration when the entry vehicle includes the cargo, orbit maneuver propulsion, and/or the main upper stage launch propulsion subsystem. This division presents a very "gray area" in that one must decide where the crew section ends and the cargo/propulsion section begins. Or more significantly, at what size or weight does a section become large enough to be considered a cargo/propulsion section. The minimum cargo requirement for the OCPDM study is 20,000 pounds and is considered large enough to classify the section carrying the payload to be cargo/propulsion section for all integral configurations. The aerodynamic surfaces are the fixed and movable surfaces of the M2/F2. Thermal protection includes the exterior panels and the insulation.

Two classifications of mission modules are defined:

1. Simple adapter which is a nonentry structure containing no equipment or cargo.

2. Cargo/Propulsion Section which is nonentry structure housing equipment and cargo.

Past experience and cost history indicates that the physical characteristics which affect the structural fabrication costs are: weight, type of material, type of construction, number and type of component parts, and application or usage.

The plot of the data and the analysis of the structure was based on structural weight being the primary parameter. Before the cost history of the vehicles was compared, it was normalized to a common base for type of material and construction. Table 6-1 presents a summary of the relative complexity factors that have been developed for the OCPDM study. A total structural complexity factor is calculated from the individual values given in Table 6-1 by summing the products of the individual values and the corresponding structural weight percentage distribution. For example, the complexity factor for a sheet stringer with frames structure that consists of 50% aluminum and 50% stainless steel is 1.25: (.50 x 1.0 + .50 x 1.5= 1.25). The analysis of the entry vehicle crew section was based on the Gemini entry vehicle, Mercury entry vehicle, and the F-4 forward fuselage. The data were first normalized for type of material and construction to aluminum sheet-stringer with frames. At this point a comparison of the Gemini entry vehicle and the Mercury entry vehicle revealed that the most outstanding difference was the amount of hatches and access doors that are provided in the structure. The Gemini vehicle has about 35% of its total wetted area that is hatches or access doors as compared to the Mercury vehicle at about 8%. Having corrected the cost for type of material and construction, the remaining cost difference was attributed to the hatches and doors. Several forms of the equation were investigated and the results checked with the F-4 forward fuselage cost. This analysis resulted in the following factor for access area:

$$KA = \frac{(4)\ (\text{Area Hatches and Doors})}{\text{Total Wetted Area}} + 1$$

The area factor is one measure of cost sensitivity to the type of component parts that make up the structural subsystem. Figure 6-1 is a plot of the CER's as adjusted for type of material and construction and the access area factor.

Although fairly reasonable correlation was obtained between the three data points (Mercury, Gemini, and F-4), the application of the area factor below

Table 6-1

Type of Material and Construction Complexity Factors

Type Material \ Type Construction	Single Skin With Frames	Sheet Stringer With Frames	Single-Skin Corrugations With Frames
Aluminum	.9	1.0	1.2
Stainless Steel	1.4	1.5	1.9
Magnesium	1.5	1.7	2.1
Titanium	2.0	2.2	2.8
Inconel-718	2.2	2.4	3.0
L-605	2.2	2.4	3.0
Rene' 41	2.6	2.9	3.6
TD-NiC	3.2	3.5	4.5
Miscellaneous	1.1	1.1	1.1

8% is questionable and requires additional investigation. The area factor is based on limited data and is a strong multiplier and therefore, must be used with caution. The following equation then applies to an entry vehicle crew section structural cost.

$$C = 3950(WSCSP)^{.766}(KMCSP)(KACSP)$$

where

C = Entry Vehicle Crew Section first unit procurement cost, dollars

WSCSP = Entry Vehicle Crew Section Structural Weight, Lbs.

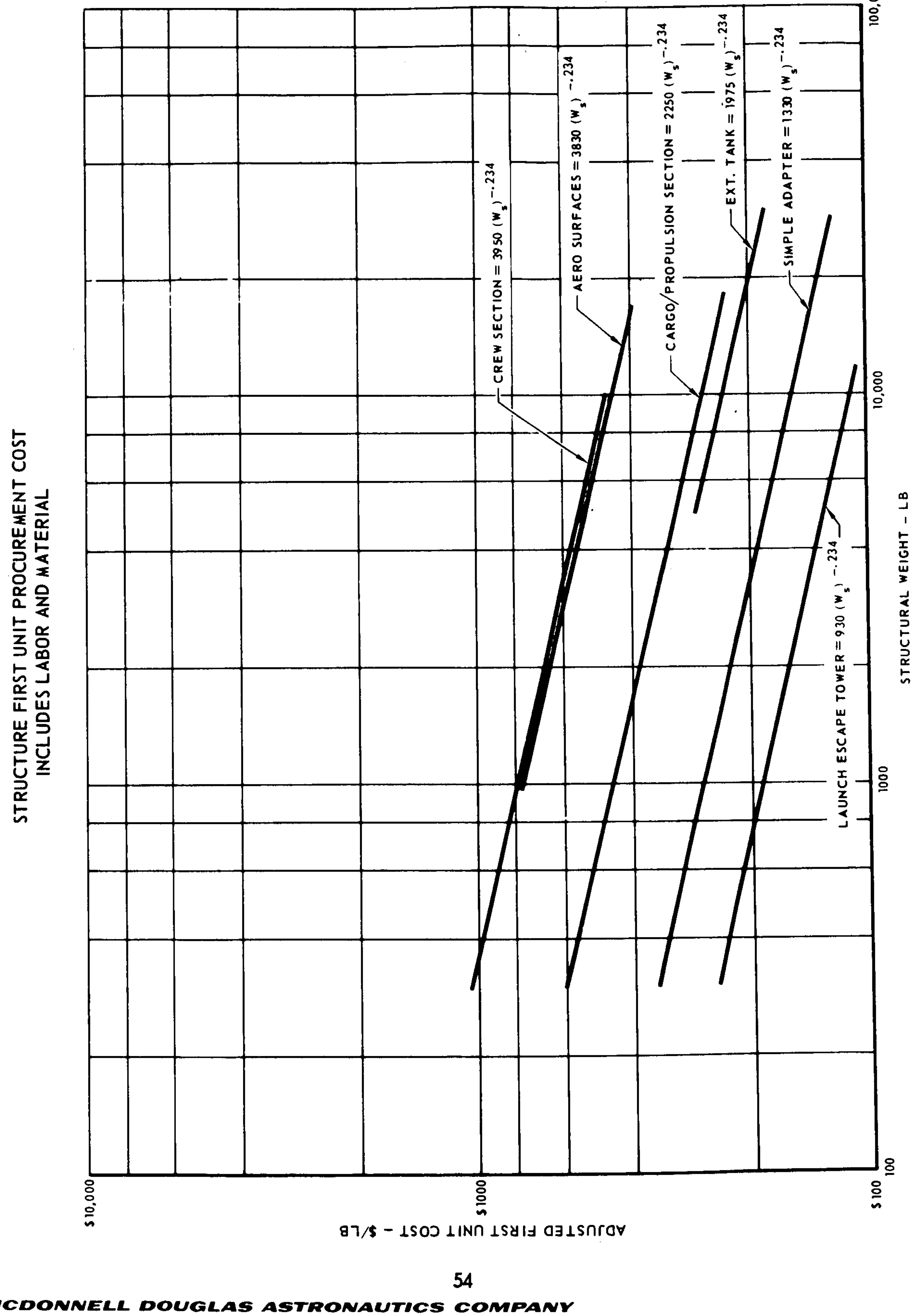
KMCSP = Type of Material and Construction Complexity Factor. See Table 6-1.

KACSP = Access Area Complexity Factor

$$= \frac{4 \text{ Area Hatches \& Doors}}{\text{Total Wetted Area}} + 1$$

Specific cost data for the entry vehicle cargo/propulsion section does not exist and therefore, this section has to be estimated from cost history of other structure. The analysis compares the F-4 forward fuselage (manned, pressurized, with densely packed equipment) to the center and aft fuselage (unpressurized propulsion section) along with the S-IVB structure (excluding the tanks) and the Gemini and Mercury data. All data was first normalized for type of material and construction to aluminum sheet-stringer with frames. The access area factor as developed from the crew section analysis was then applied to the data. The area ratio for the Gemini adapter is 13% and the F-4 aft and center

Figure 6-1


STRUCTURE FIRST UNIT PROCUREMENT COST
INCLUDES LABOR AND MATERIAL
CREW SECTION = 3950 $(W_s)^{-.234}$
AERO SURFACES = 3830 $(W_s)^{-.234}$
CARGO/PROPULSION SECTION = 2250 $(W_s)^{-.234}$
EXT. TANK = 1975 $(W_s)^{-.234}$
SIMPLE ADAPTER = 1330 $(W_s)^{-.234}$
LAUNCH ESCAPE TOWER = 930 $(W_s)^{-.234}$
100,000
10,000
1000
100
STRUCTURAL WEIGHT - LB
$10,000
$1000
$100
ADJUSTED FIRST UNIT COST - $/LB

fuselage is 16%. The S-IVB data was not adjusted because the area ratio is only about 1%. The S-IVB structural cost data is segregated into 4 major sections.

1. Propellant tank
2. Skirts
3. Thrust Structure
4. Aft Interstages

The skirts and thrust structure are comparable to the Gemini adapter and the F-4 aft and center fuselage. All the sections are non-entry structures housing equipment. The aft interstage is non-entry structure with no equipment and therefore, falls in the category of the simple adapter.

The relative costs of the simple adapter type of structure and the cargo/propulsion type of structure is due to the application or usage of the structure. The relative cost of a section of structure housing equipment reflects the provisions added to accommodate equipment mounting such as clips, intercostals, and stand-offs as well as the basic structrue that is built from many components. This compares to the aft interstage structure that is constructed with relatively large but few types of parts. The significant fact here is that the manufacturing cost of the structural subsystem is highly sensitive to the number and type of component parts that make up the structure. This could be further related to the number of component parts per pound of structure, however, a parts count for structure is rarely, if ever, available. Since the application or usage of a structure cannot be specifically quantified the various structural sections to be estimated can only be grouped by family or ranked according to their relative complexity and cost.

For the entry vehicle cargo/propulsion section, a comparison of the F-4 aft and center fuselage to the S-IVB skirts and the Gemini adapter was made. The data shows fairly reasonable correlation; however, the Gemini adapter is higher than the other cost data. The major reasons for this difference are that the adapter has three separation planes and the ECS radiator is an integral part of the adapter structure, both contributing to the relatively higher cost. The CER developed for the cargo/propulsion section includes the same parameters as the crew section, however, the relative cost is about 60% of the crew section. Again, this cost difference is due to the type of components and application or usage. The entry vehicle cargo/propulsion CER is given below.

$$C = 2250(WSCPP)^{.766}(KMCPP)(KACPP)(KPS)$$

where

C = E/V Cargo/Propulsion Section First Unit Procurement Cost, dollars

WSCPP = E/V Cargo/Propulsion Section Structural Weight, Lbs.

KMCPP = Type of Material and Construction Complexity Factor. See Table 6-1.

KACPP = Access Area Complexity Factor

$$= \frac{4 \text{ Area Hatches \& Doors}}{\text{Total Wetted Area}} + 1$$

KPS = Type of Propellant Complexity Factor. (This factor is only applicable when the propellant tanks for the launch upper stage are an integral part of the basic structure, applies only to the M2/F2 configuration).

KPS = 1.00 Storable Propellants
1.25 Cryogenic Propellants

The aerodynamic control surfaces are based on the F-4 cost data as a function of weight and type of material and construction.

$$C = 3830(\text{WSACSP})^{.766}(\text{KMACSP})$$

where

C = Entry Vehicle Control Surfaces First Unit Procurement cost, dollars

WSACSP = Structural weight of the Aerodynamic Control Surfaces, lbs.

KMACSP = Type of Material and Construction Complexity Factor. See Table 6-1.

The launch escape tower is a truss structure and is estimated to be 70% of the cost of a sheet-stringer with frames simple adapter. Specific cost data were not available for this item.

$$C = 930(\text{WSLET})^{.766}$$

where

C = Launch Escape Tower Structure First Unit Procurement Cost, dollars

WSLET = Launch Escape Tower Structural Weight, lbs.

The mission module as stated previously has two classifications; simple adapter and cargo/propulsion section. The mission module may contain one or both types of structure. The analysis and CER developed for the entry vehicle cargo/propulsion section are applicable to the mission module cargo/propulsion section. The relative cost estimate for the mission module will always be less than the entry vehicle because of the type of material and construction complexity factor. The propellant factor is deleted since the mission module structure will not serve as an integral propellant tank.

$$C = 2250(WSCPM)^{.766}(KMCPMP)(KACPMP)$$

where

C = M/M Cargo/Propulsion Section First Unit Procurement Cost, dollars

WSCPM = M/M Cargo/Propulsion Section Structural Weight, Lbs.

KMCPMP = Type of Material and Construction Complexity Factor. See Table 6-1.

KACPMP = Access Area Complexity Factor.

$$= \frac{4 \text{ Area Hatches and Doors}}{\text{Total Wetted Area}} + 1$$

The simple adapter CER is based on the S-IVB aft interstage structure. Since the simple adapter does not have equipment mounted in it, the need for access doors is limited and will always be a very small percentage of the total area. The access area factor is therefore deleted from the CER.

$$C = 1330(WSA)^{.766}(KMAP)$$

where

C = Mission Module Simple Adapter First Unit Procurement Cost, dollars

WSA = Simple Adapter Structural Weight, Lbs.

KMAP = Type of Material and Construction Complexity Factor. See Table 6-1.

The integral versions, configurations D, E, and F, require large propellant tanks. For the M2/F2 the tanks are an integral part of the basic structure for configurations E and F and are external expendable tanks for configuration D. All of the ballistic vehicles for configurations D, E, and F have separate tanks. These large separate tanks for the launch upper stage propulsion subsystem are classified as structural items. The CER for these tanks is based on a previous analysis and a point design and estimated cost of a tank. The estimated cost is slightly less than S-IVB stage since the S-IVB stage has integrally stiffened structure vs. a monocoque design for the tank defined for the point design and this study. The CER is based on tank weight and type of propellant.

$$C = 1975(WLEXT)^{.766}(KPT)$$

where

C = Upper Stage Propellant Tank First Unit Procurement Cost, dollars

WLEXT = Total Weight of a Tank, Lb. (Refer to symbol dèfinitions, Appendix D for clarification of symbols).

KPT = Type of Propellant Complexity Factor.
= .80 Storable Propellants
= 1.00 Cryogenic Propellants

As stated previously, the structural cost includes the prime contractor's labor, procured materials, and subcontract effort. Since it is desirable to estimate and analyze labor and material separately because of changing labor rates, the developed CER's are further modified to estimate these two cost categories separately. Separation of these two cost categories is based on the data presented in Figure 6-2.

As an example the modified equation for the entry vehicle crew section is shown here.

$$\text{Labor Cost} = 335(\text{WSCSP})^{.766}(\text{KMCSP})(\text{KACSP})[1 - .05(\text{KMCSP})](\text{KPROD})$$

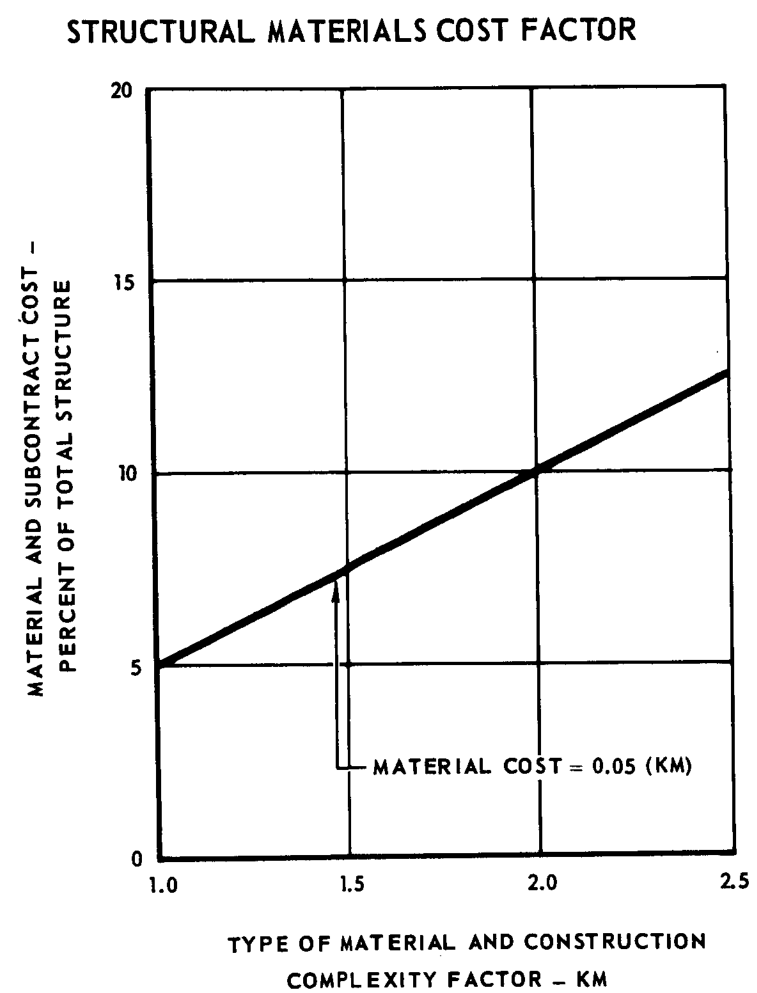
$$\text{Material Cost} = 3950(\text{WSCSP})^{.766}(\text{KMCSP})(\text{KACSP})(.05)(\text{KMCSP})(\text{KMCS})$$

KPROD is a production labor rate factor. The constant in the equation has been adjusted to account for the addition of the labor rate factor (3950/11.80 = 335). KMCS is an economic escalation factor. All of the structural CER's were modified as outlined above.

6.1.3.2 Final Assembly and Checkout - Final assembly and checkout includes the final major assembly of the structure and the acceptance test of the spacecraft. From the Gemini cost history it has been found that the acceptance test of the complex subsystems is a very high cost area in relation to the structure. For this reason and the fact that the size range of the vehicles to be estimated is so large, the CER is written in two parts. One part is a function of the structural costs and the other a function of the remaining subsystems. The final assembly and checkout cost has been related to the production costs of the subsystems and is 6% of the structure subsystem and 96% of the remaining subsystems.

6.1.4 Material, Contractor Furnished Equipment (CFE), and Subcontract - This cost category includes the raw material, purchased parts, castings and forgings, minor subcontract, and major subcontract costs. A CER has been developed for each subsystem as outlined in the following paragraphs. An economic escalation factor (KMCS) is provided for each CER.

Figure 6–2


STRUCTURAL MATERIALS COST FACTOR
MATERIAL AND SUBCONTRACT COST – PERCENT OF TOTAL STRUCTURE
20
15
10
5
0
1.0
1.5
2.0
2.5
MATERIAL COST = 0.05 (KM)
TYPE OF MATERIAL AND CONSTRUCTION COMPLEXITY FACTOR – KM

6.1.4.1 Sustaining Engineering and Tooling - Materials cost are required in support of engineering and tooling during the production of the vehicles. These costs are relatively small, and based on past aircraft history, have shown a good correlation to manhours expended. Engineering is $.10 per sustaining engineering manhour while tooling is at $1.00 per sustaining tooling manhour.

6.1.4.2 Structure Subsystem - The materials cost for this subsystem have been discussed with the prime contractor production labor costs in Section 6.1.3.

6.1.4.3 Thermal Protection System - The CER's for the thermal protection system are based on the Gemini cost history, a detail cost analysis performed by the MDAC-ED Producibility Department, and the work of Ref. 6-1. The Gemini data and the Ref. 6-1 report were used to establish the basic cost of the panels. The producibility study was used to establish the relative cost factors for the various materials. The CER's and data presented here represent the cost of procurring a fabricated panel and the necessary retainers and fasteners.

$$C = 720(KMTP)(KS)(PS)^{-.322}(SWTP)$$

where

C = First Unit cost of thermal protection system panels, dollars

KMTP = Material complexity factor (see Table 6-2).

KS = Panel shape complexity factor (see Table 6-3).

PS = Average Panel size, sq. ft per panel.

SWTP = Total area, thermal protection system.

Table 6-2

Material Complexity Factor Thermal Protection System

Type Material	Factor
Aluminum	1.2
Titanium	2.8
Inconel 718	3.0
Rene' 41	3.6
TD-NiC	4.5
Coated Columbium	20.0
Coated Molybdenum	20.0
Ablative S-20T	4.5

Table 6-3

Panel Shape Complexity Factor			
Panel Type	Flat	Simple Curvature	Compound Curvature
Radiative	1.0	1.10	1.25
Ablative	1.0	1.20	1.45

The aluminum, titanium, inconel, Rene'41 and TD nickel chromium panels are single-face corrugated resistance welded panels. The columbium and molybdenum panels are coated single-face corrugated electron beam welded panels. The ablative panel is a low density ablative filler in reinforced phenolic honeycomb. Figure 6-3 presents the cost of flat panels vs. panel size.

6.1.4.4 Water Cooling Subsystem - Cost data for this subsystem are not available. The CER developed for the hydraulic and pneumatic subsystem is used here.

6.1.4.5 Landing Gear - The landing gear CER is based on the F-4 aircraft with weight as the estimating parameter. See Figure 6-4.

6.1.4.6 Inflatable Aerodynamic Devices - The CER for the parachute is based on the Gemini cost history. Cost data were not available for the sailwing. The sailwing has been "estimated" at 1.5 times the parachute cost. See Figure 6-5.

6.1.4.7 Power Supply and Ordnance - The CER for the electrical distribution system and the ordnance system is based on the Gemini cost history. The weight advantage curve has not been applied since weight increase or decrease for these two items is primarily due to a change in the number of components. See Figure 6-6.

The fuel cell CER is based on the Gemini cost history and Allis Chalmers data with power output as the estimating parameter. See Figure 6-7.

The battery CER is a function of the required energy per battery and the number of batteries.

The reactant supply system is based on Gemini history with total energy output (kilo-watt hours) as the estimating parameter. The exponent was established by an analysis of how the energy output varies with tank volume. Cost history from tanks vs. volume was then applied to energy output to establish the

Figure 6–3

THERMAL PROTECTION SYSTEM
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT

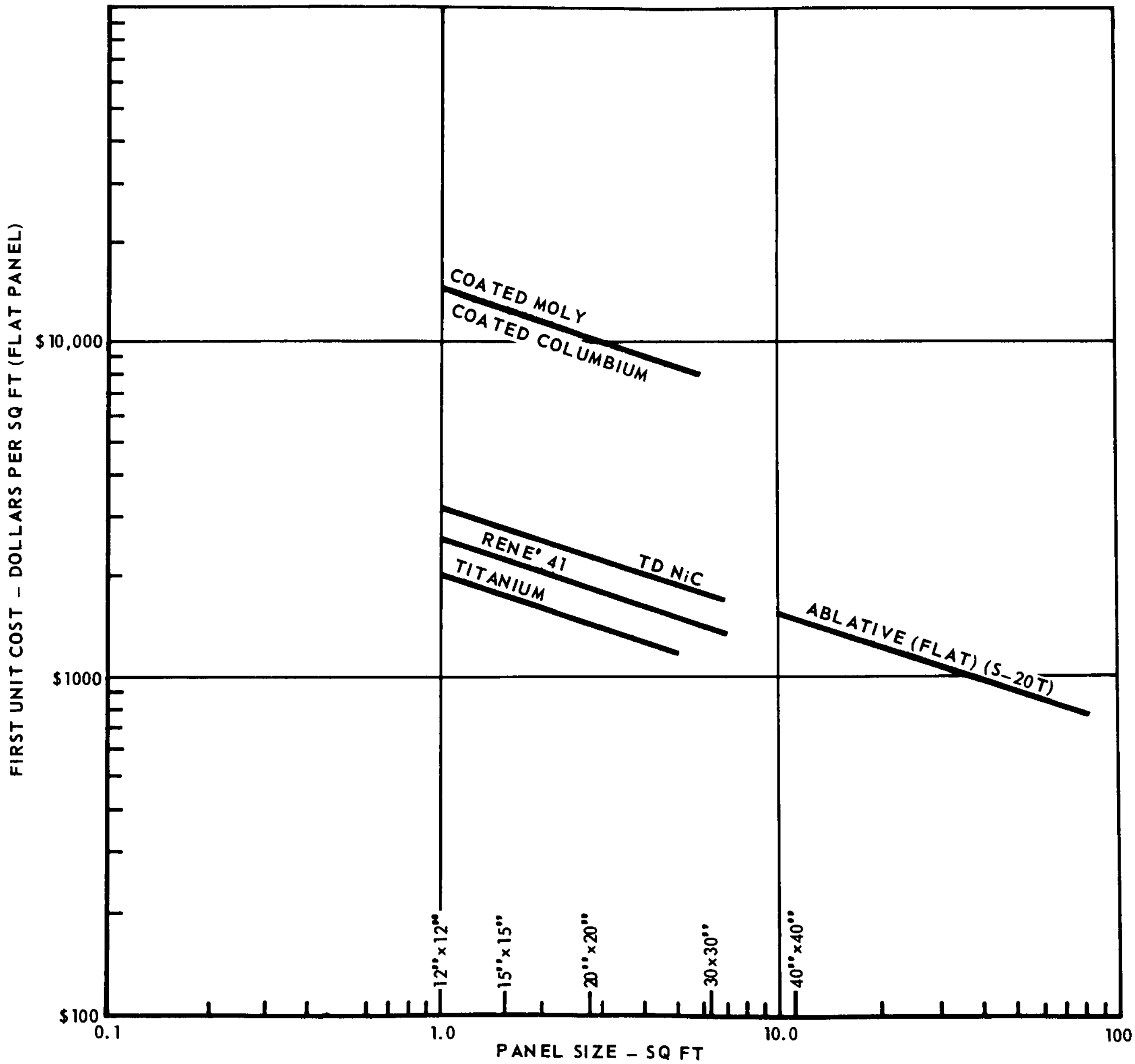


Figure 6-4

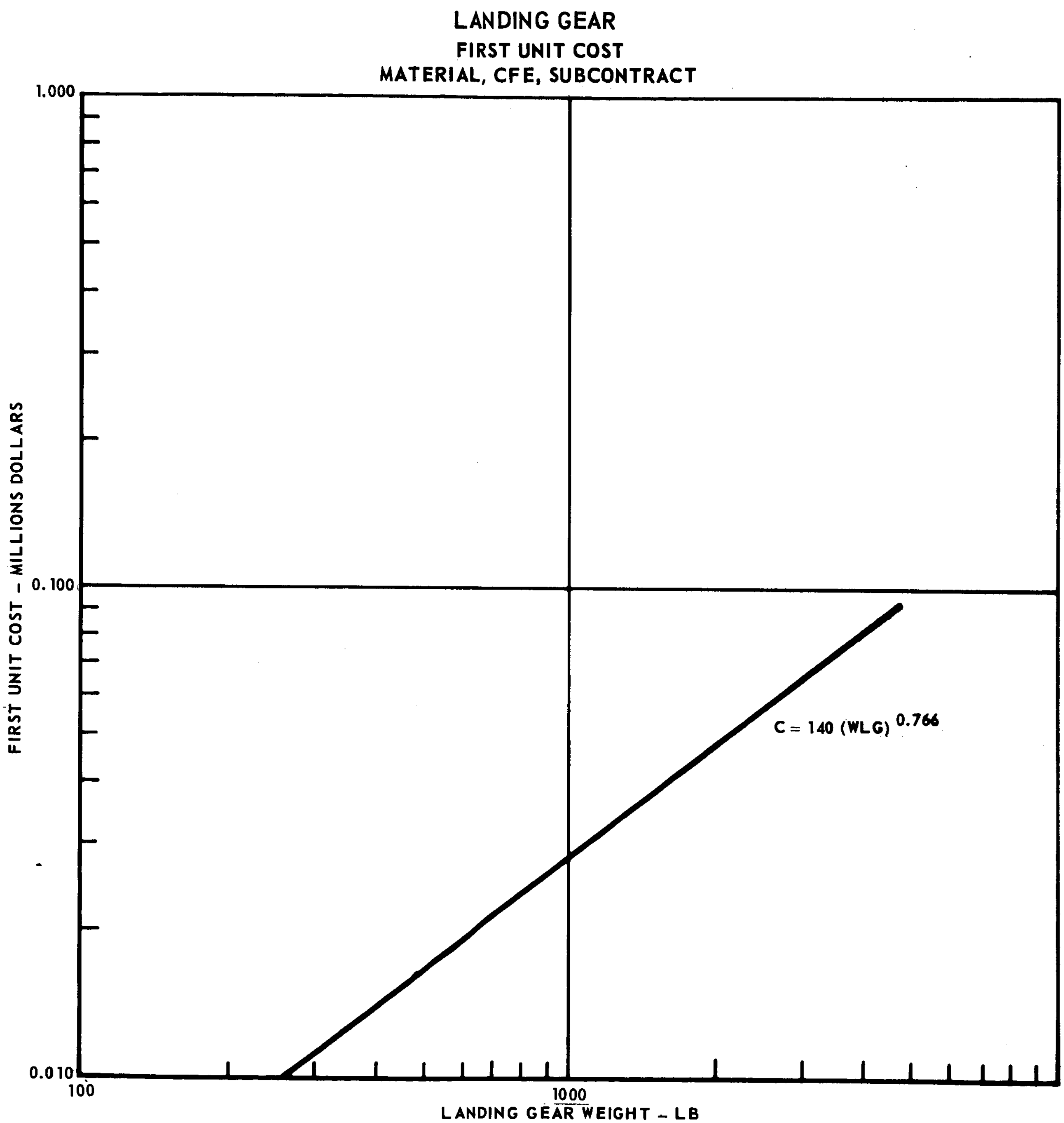

LANDING GEAR
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT
1.000
0.100
0.010
FIRST UNIT COST - MILLIONS DOLLARS
100
1000
LANDING GEAR WEIGHT - LB
C = 140 (WLG) 0.766

Figure 6-5

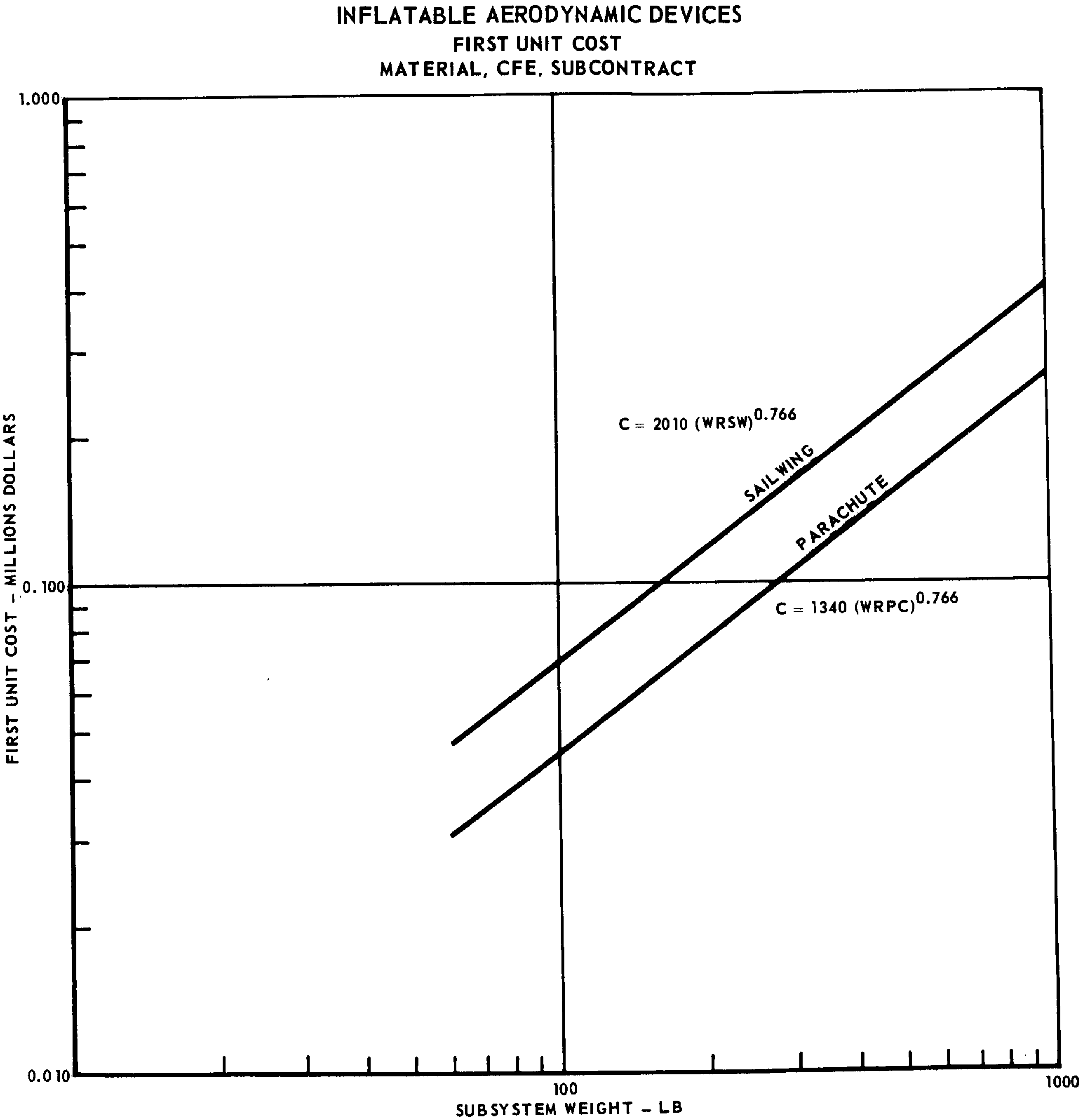

INFLATABLE AERODYNAMIC DEVICES
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT
FIRST UNIT COST – MILLIONS DOLLARS
1.000
0.100
0.010
SUBSYSTEM WEIGHT – LB
100
1000
C = 2010 (WRSW)0.766
SAILWING
PARACHUTE
C = 1340 (WRPC)0.766

Figure 6-6

POWER SUPPLY
ELECTRICAL DISTRIBUTION & ORDNANCE
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT

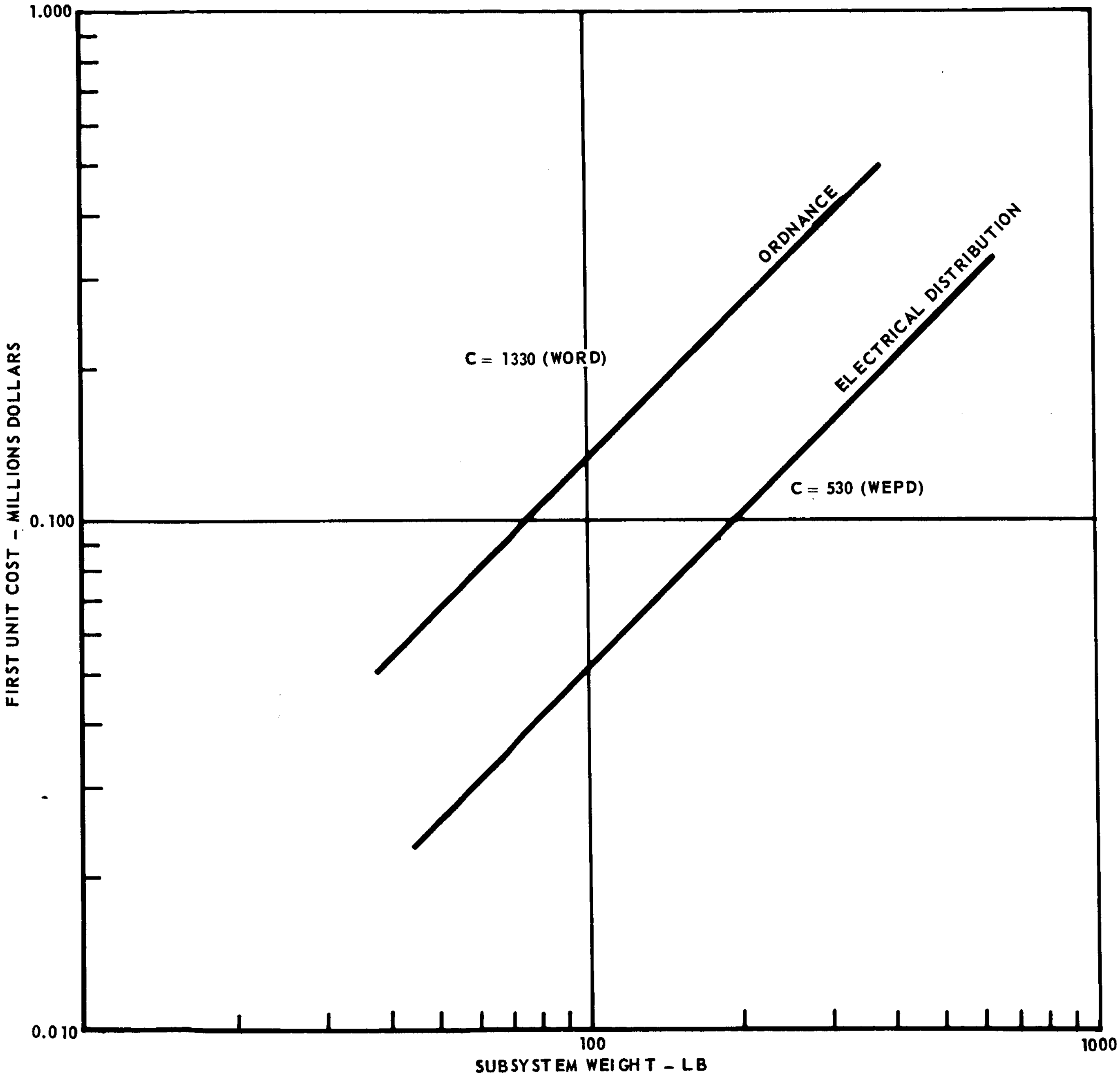
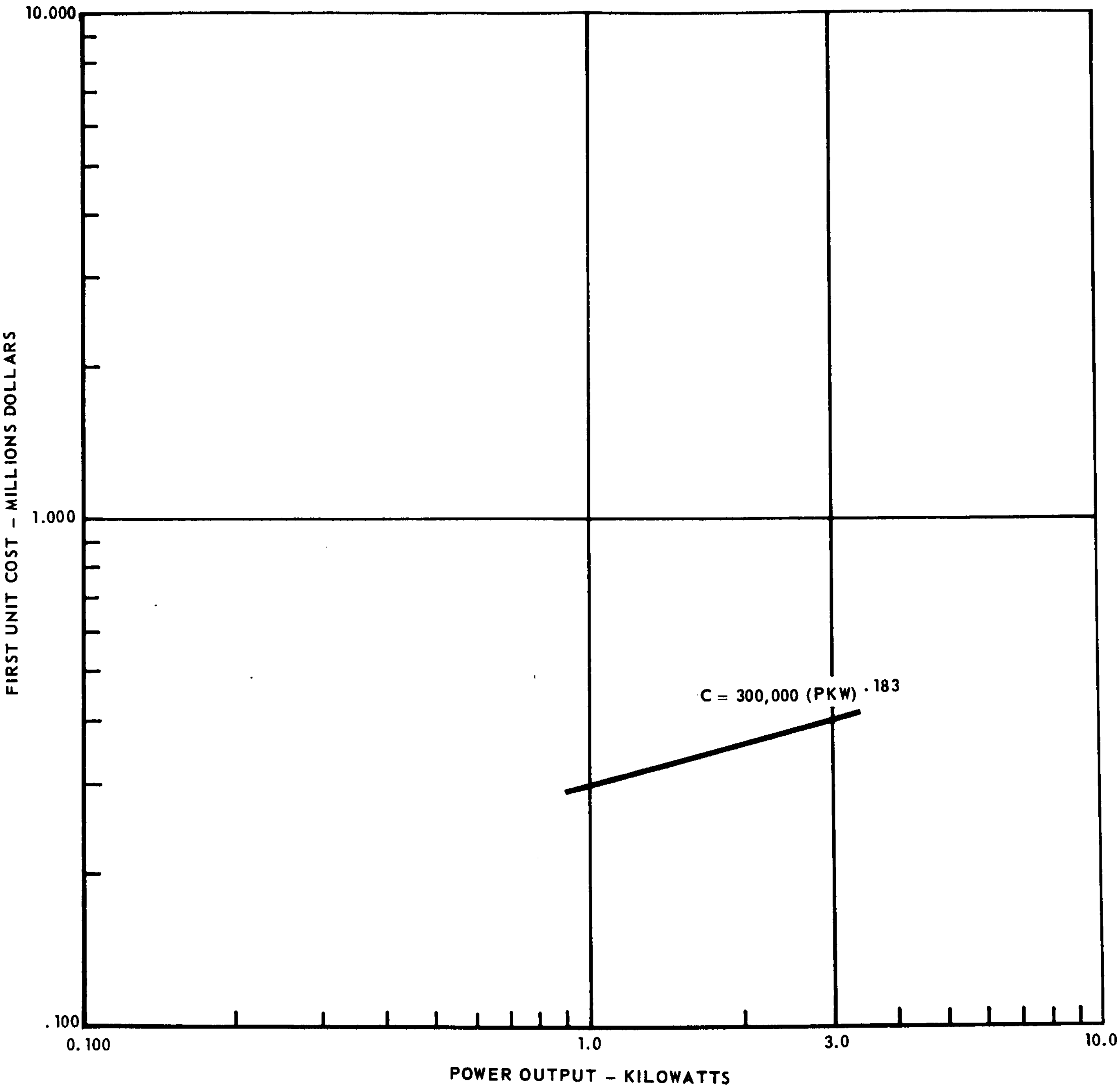


Figure 6-7

POWER SUPPLY - FUEL CELL
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT



exponent. See Figure 6-8.

Hydraulics and pneumatics costs are based on the F-4. See Figure 6-9.

6.1.4.8 Environmental Control and Life Support - The CER for the Environmental Control System (ECS) is based on Gemini history and vendor data obtained as part of a previous study. The analysis performed separates the cost history into 12 major component groups that make up the ECS subsystem. The resulting CER reflects how the total subsystem cost varies with the number of men and the mission time. Two CER's were developed, one is for a storable gas supply and the other is for a cryogenic gas supply. A mission time of one (1) day is the minimum acceptable input to the CER. The CER calculates the cost of the total environmental control system. This total cost is then allocated between the entry vehicle and mission module dependent on the weight distribution. See Figures 6-10 and 6-11.

Furnishings and equipment includes unrelated types of equipment such as suits, personal parachutes, food containers, first aid, survival kit, and crew accessories. On past programs some of this equipment has been government furnished (GFE) and some has been contractor furnished (CFE). A cursory examination of the cost of the items indicates about $650 per pound and is used for the CER.

6.1.4.9 Avionics - The avionics subsystems as defined are only sensitive to concept and vehicle configuration, therefore, the requirement for a CER is questionable. Rather than developing a CER, estimates have been made for the different avionic concepts and a fixed cost is used dependent on the users selection of one of the concepts.

The following values were estimated, based on Gemini cost history and vendor supplied data, for the concepts as defined in Volume II Book 1.

Guidance and Control

Concept	First Unit Cost
GC-1 or 5	$2,844,000
GC-2 or 6	3,775,000
GC-3 or 7	4,433,000
GC-4 or 8	5,348,000

Telecommunication

Concept	First Unit Cost
TC-1	$2,206,000
TC-2 or 4	2,758,000
TC-3 or 5	2,398,000

Figure 6-8

POWER SUPPLY – REACTANT SUPPLY SYSTEM
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT

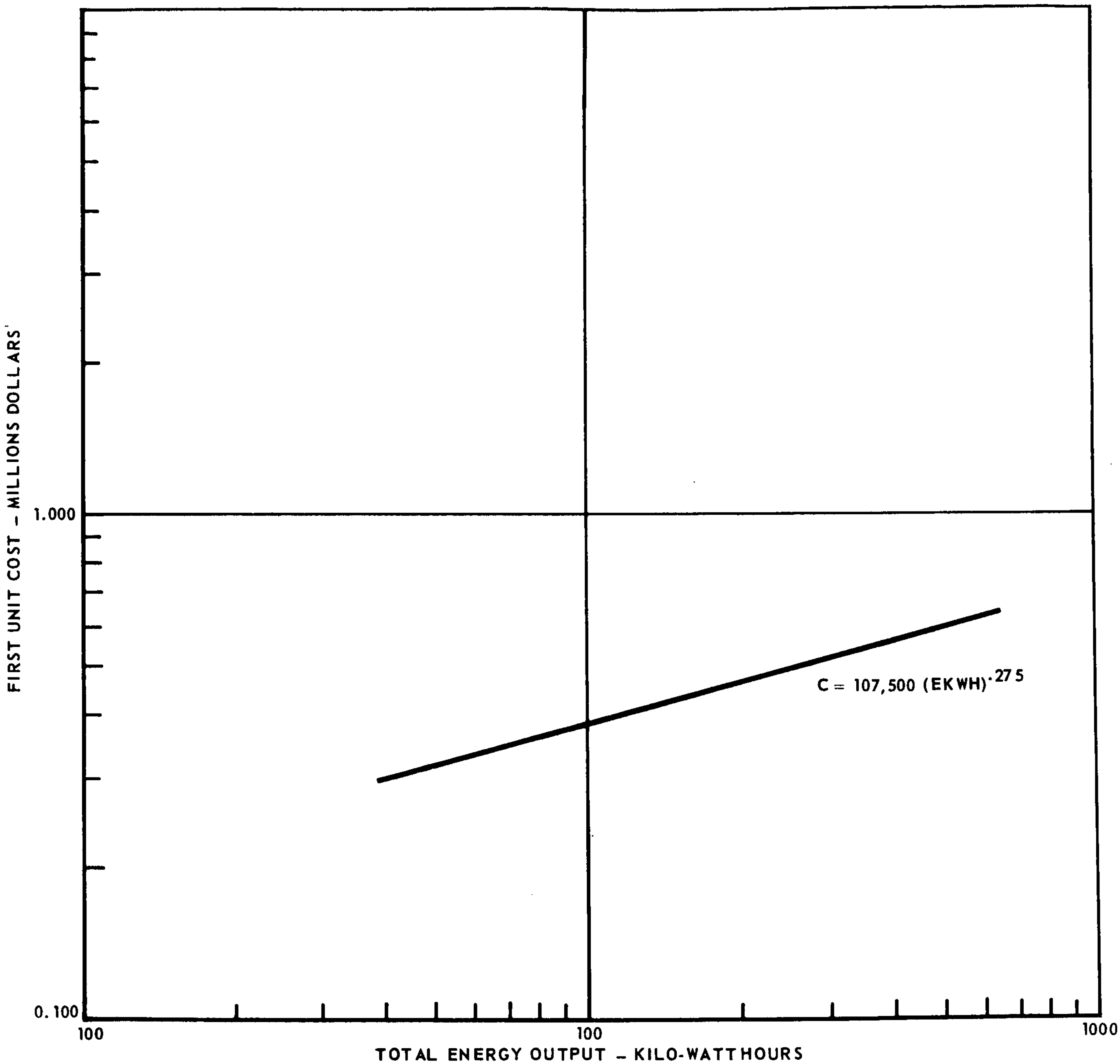


Figure 6–9

POWER SUPPLY – HYDRAULICS AND PNEUMATICS
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT

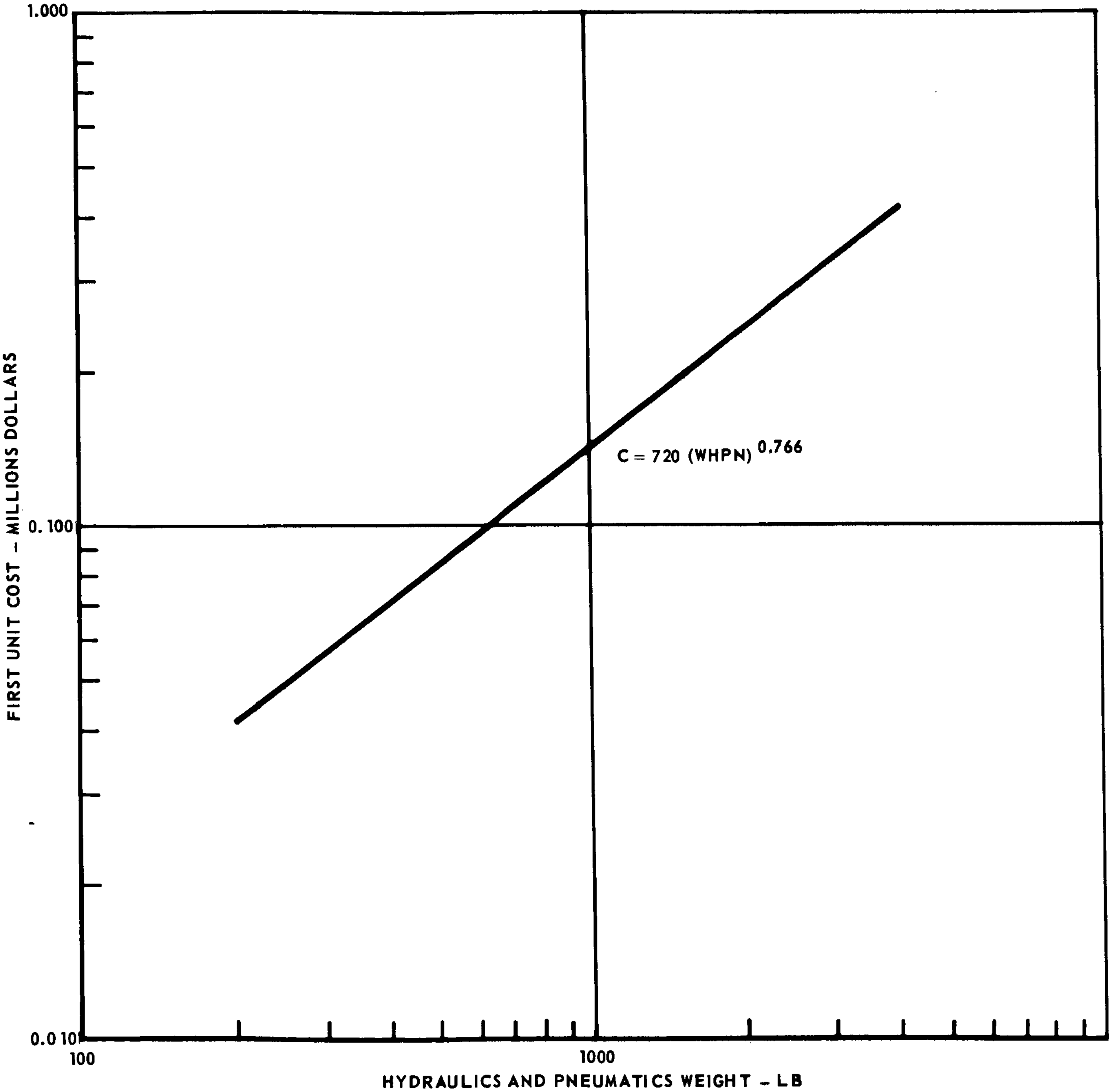


Figure 6-10

ENVIRONMENTAL CONTROL SYSTEM
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT
STORABLE GAS SUPPLY

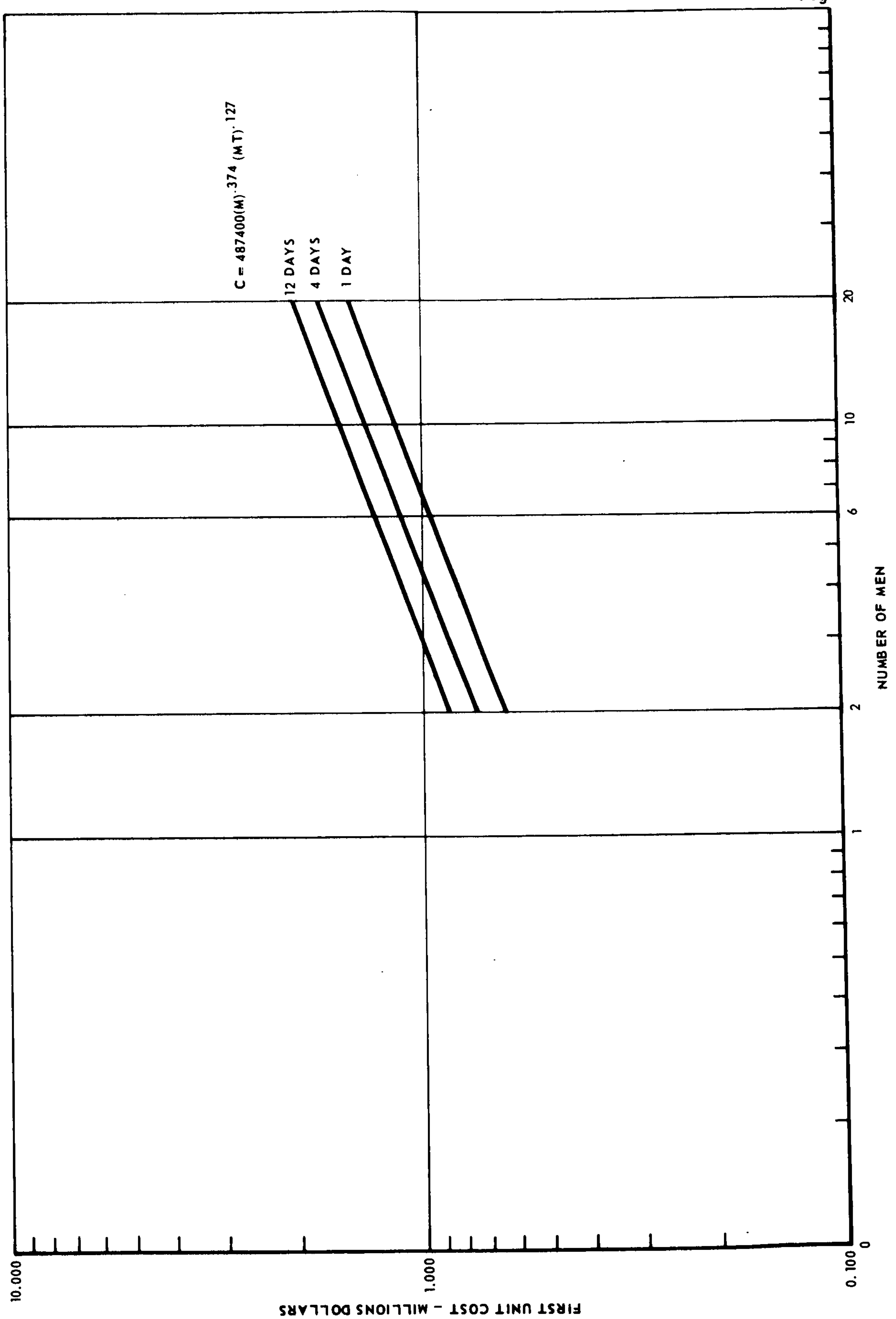


Figure 6-11

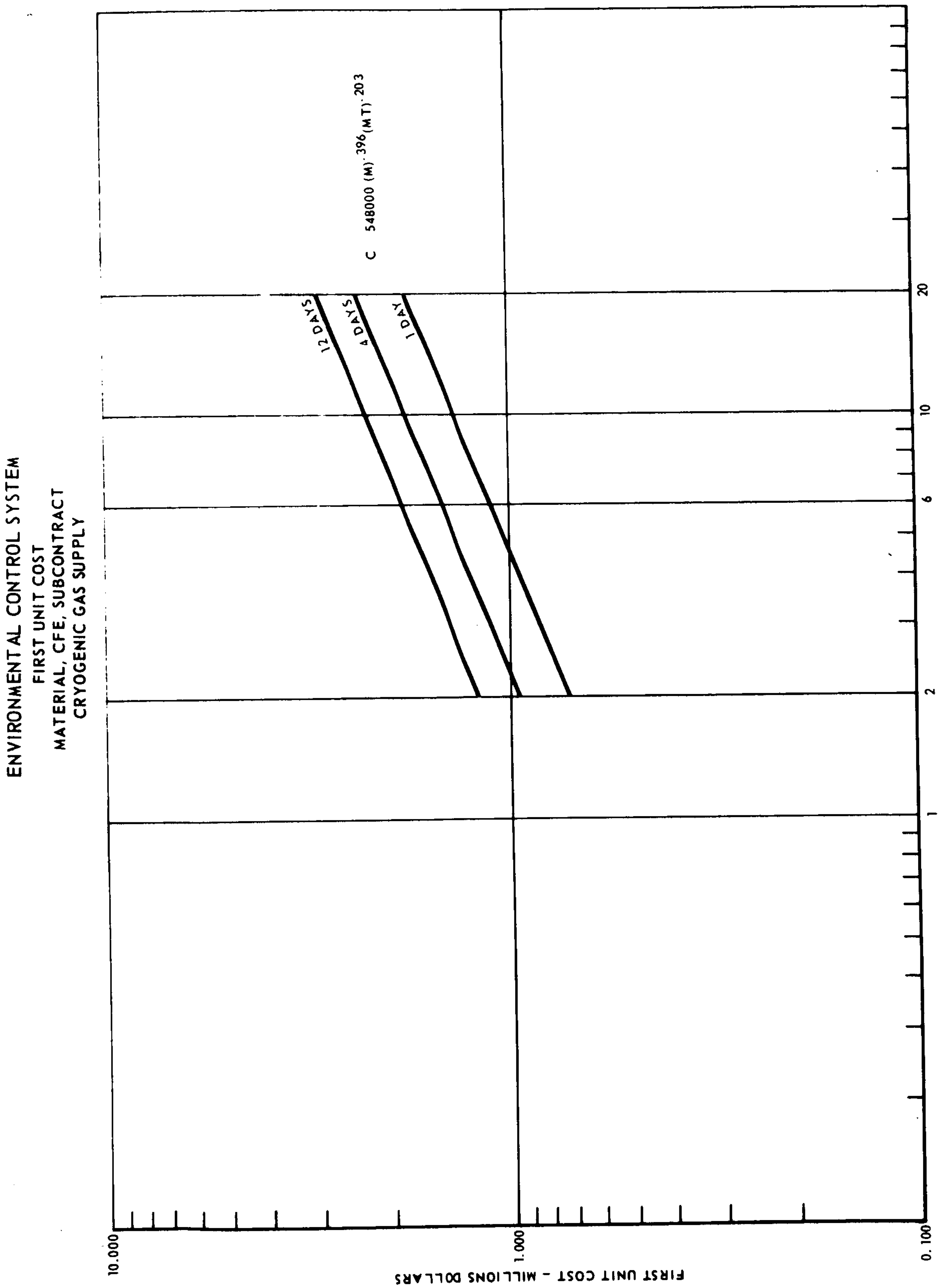
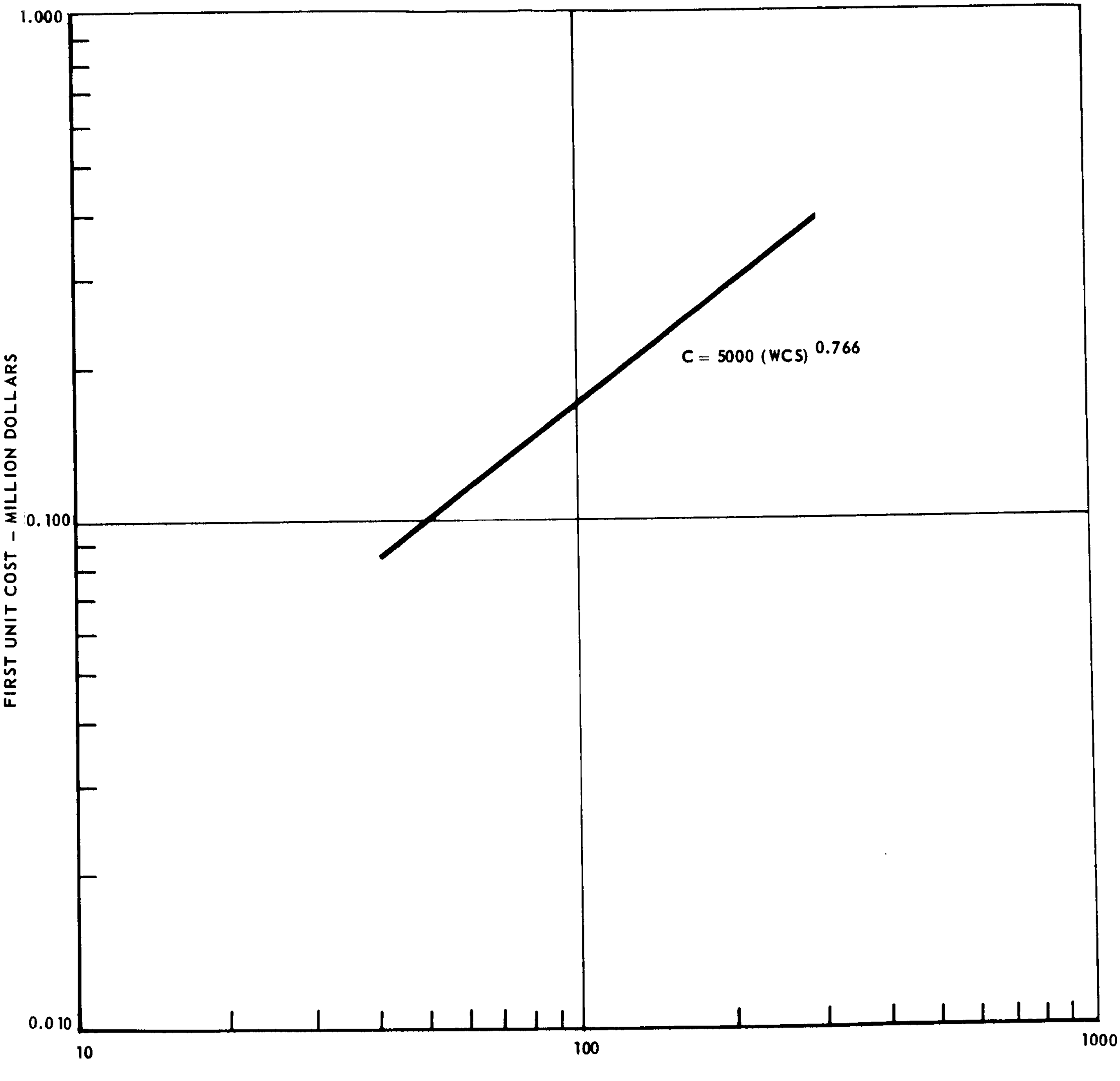

ENVIRONMENTAL CONTROL SYSTEM
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT
CRYOGENIC GAS SUPPLY
C 548000 (M)^.396 (MT)^.203
12 DAYS
4 DAYS
1 DAY
NUMBER OF MEN
1
2
6
10
20
FIRST UNIT COST - MILLIONS DOLLARS
10.000
1.000
0.100

Figure 6-12

CREW STATION
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT



The crew station which is catalogued in the avionics group is based on the Gemini cost history and weight. See Figure 6-12.

6.1.4.10 Propulsion - The propulsion CER's have been developed by type of engine and the necessary additional components required to complete a particular propulsion subsystem. The CER's developed for each component are then used for each of the propulsion subsystems defined as applicable. Each subsystem, as applicable, is therefore sensitive to type of engine and the estimating parameters utilized.

The liquid engine subsystems are segregated into engines, tanks, and lines, valves and miscellaneous (LVM). The LVM category includes the residue of the propulsion subsystem after the engines and propellant tanks are extracted.

Four classifications of liquid rocket engines are considered, segregated as to cooling, feed system and propellant type. Only one solid rocket motor (SRM) CER was developed and is used for all the SRM applications in this study.

Figure 6-13 presents a summary of the four liquid engine first unit cost CER's. The engines have been classified as follows:

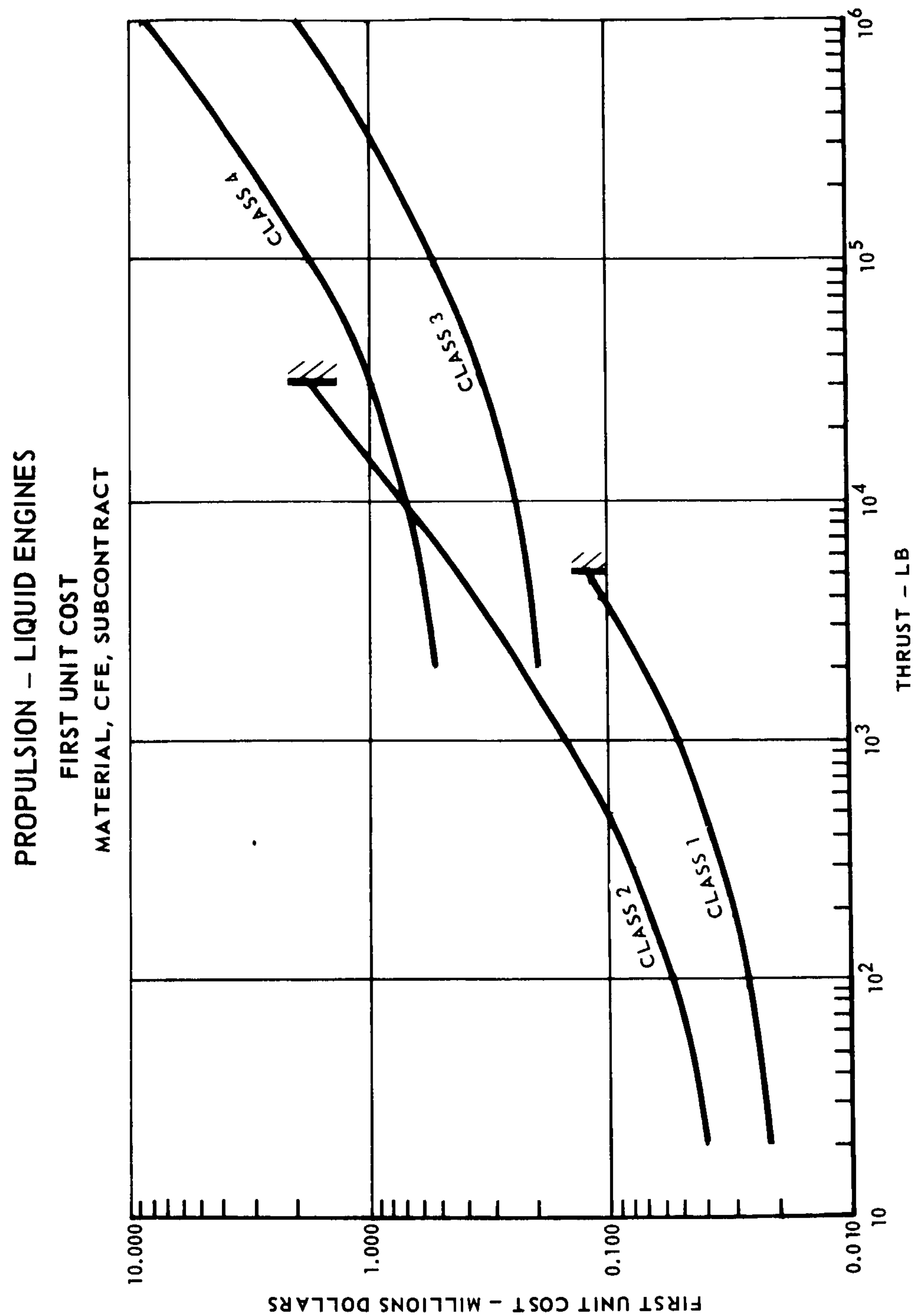
1. Radiation cooled, pressure fed, storable propellants (lowest cost)
2. Ablative cooled, pressure fed, storable propellants.
3. Regenerative cooled, pump fed, LOX/RP and storable propellants
4. Regenerative cooled, pump fed, cryogenic propellants (highest cost)

In general, pump fed engines are more expensive than pressure fed engines; regenerative cooling is more expensive than ablative or radiative cooling; ablative more expensive than radiative; and cryogenic propellants are more expensive than storable propellants. LOX/RP propellant engines are similar in their cost history to storable propellant engines and were analyzed together as one family (Class 3 engines).

The range of thrusts required for the study are great and consequently extrapolations beyond the data base of each class of engines were made. The Class 1 and 2 engines are considered for the relatively low thrust range and Classes 3 and 4 for the relatively high thrust range. A problem arises in the intermediate thrust range where all four classes of engines come into play. Care must be exercised in this thrust regime.

During the analysis, many performance parameters were considered. A

Figure 6-13


PROPULSION – LIQUID ENGINES
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT
CLASS 1
CLASS 2
CLASS 3
CLASS 4
THRUST – LB
FIRST UNIT COST – MILLIONS DOLLARS
10.000
1.000
0.100
0.010
10
10^2
10^3
10^4
10^5
10^6

regression analysis was applied to the data, using thrust, engine weight, chamber pressure, and specific impulse as the independent parameters. These parameters were considered individually as well as in various combinations but the limited data in some cases resulted in equations which exhibited trends inconsistent with physical characteristics. Therefore the technique employed involved close scrutinization of each data point and rationalizations as to why some data points are high or low relative to the majority of the data of a specific engine class. The CER's developed are the results of a faired line through the data.

Class 1 - Radiation cooled, pressure fed, storable propellants

(F = 25 - 5000)

$$C_1 = 2.0(10)^4 + 240(F)^{.700}$$

Class 2 - Ablative cooled, pressure fed, storable propellants

(F = 25 - 50,000)

$$C_1 = 3.5(10)^4 + 450(F)^{.800}$$

Class 3 - Regenerative cooled, pump fed, LOX/RP and storable propellants

$(F = 2000 - 2.0)(10)^6$

$$C_1 = 2.0(10)^5 + 113(F)^{.700}$$

Class 4 - Regenerative cooled, pump fed, LOX/H_2 propellants

$(F = 2000 - 1.0(10)^6$

$$C_1 = 3.5(10)^5 + 475(F)^{.700}$$

where

C_1 = First unit cost

F = Vacuum thrust, lbs.

The Class 1 engine CER is based on the available data and a close examination of the entire family of CER's. Sufficient data were not available to establish a CER for this class by itself. Therefore, cost values and trends of the entire family of engines was utilized for the derivation of this CER. See Figure 6-14 for a plot of the CER.

The Class 2 engine CER has a fairly good data base over the range of thrust to be estimated. Nine data points were available and a very reasonable correlation was established. This data was the basis for establishing the shape of the curve that is used for the engine CER's. See Figure 6-15.

Figure 6–14

PROPULSION – LIQUID ENGINES
RADIATION COOLED, PRESSURE FED, STORABLE PROPELLANTS (CLASS 1)
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT

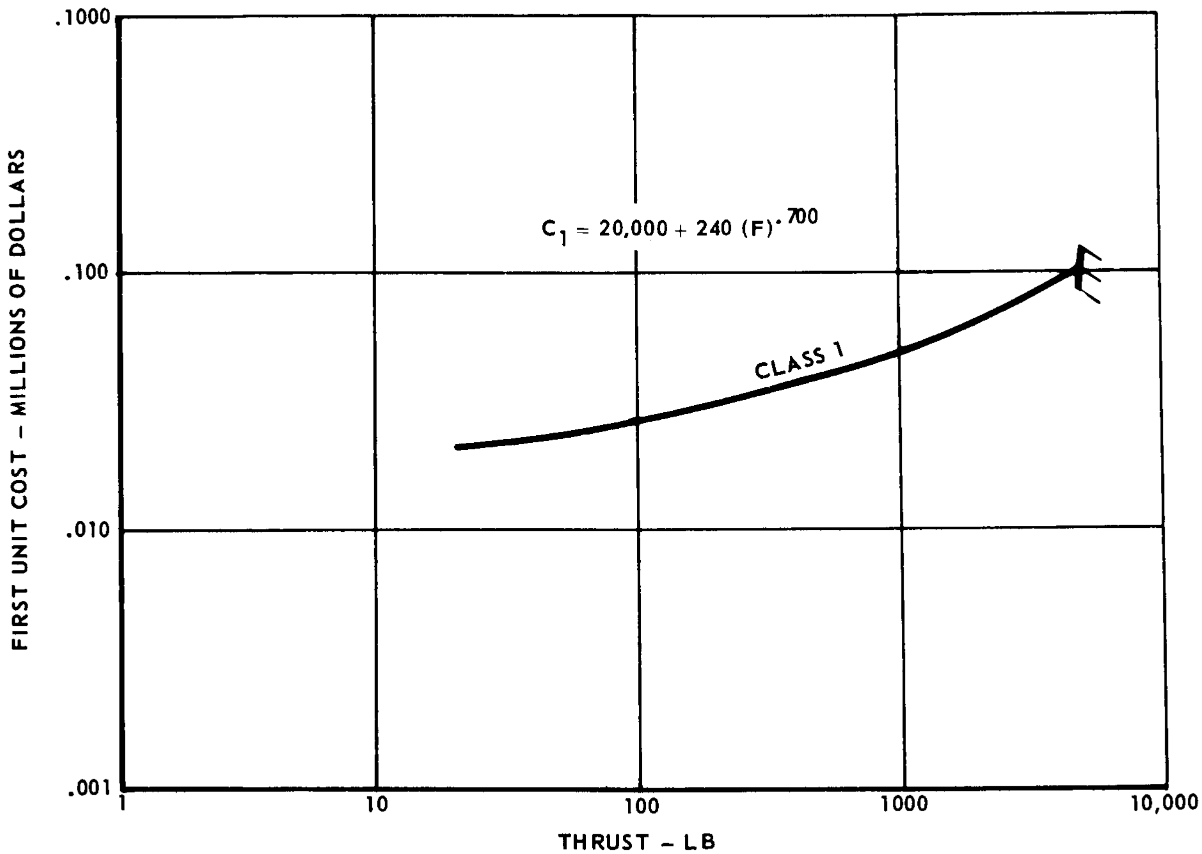


Figure 6-15

PROPULSION – LIQUID ENGINES
ABLATIVE COOLED, PRESSURE FED, STORABLE PROPELLANTS (CLASS 2)
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT

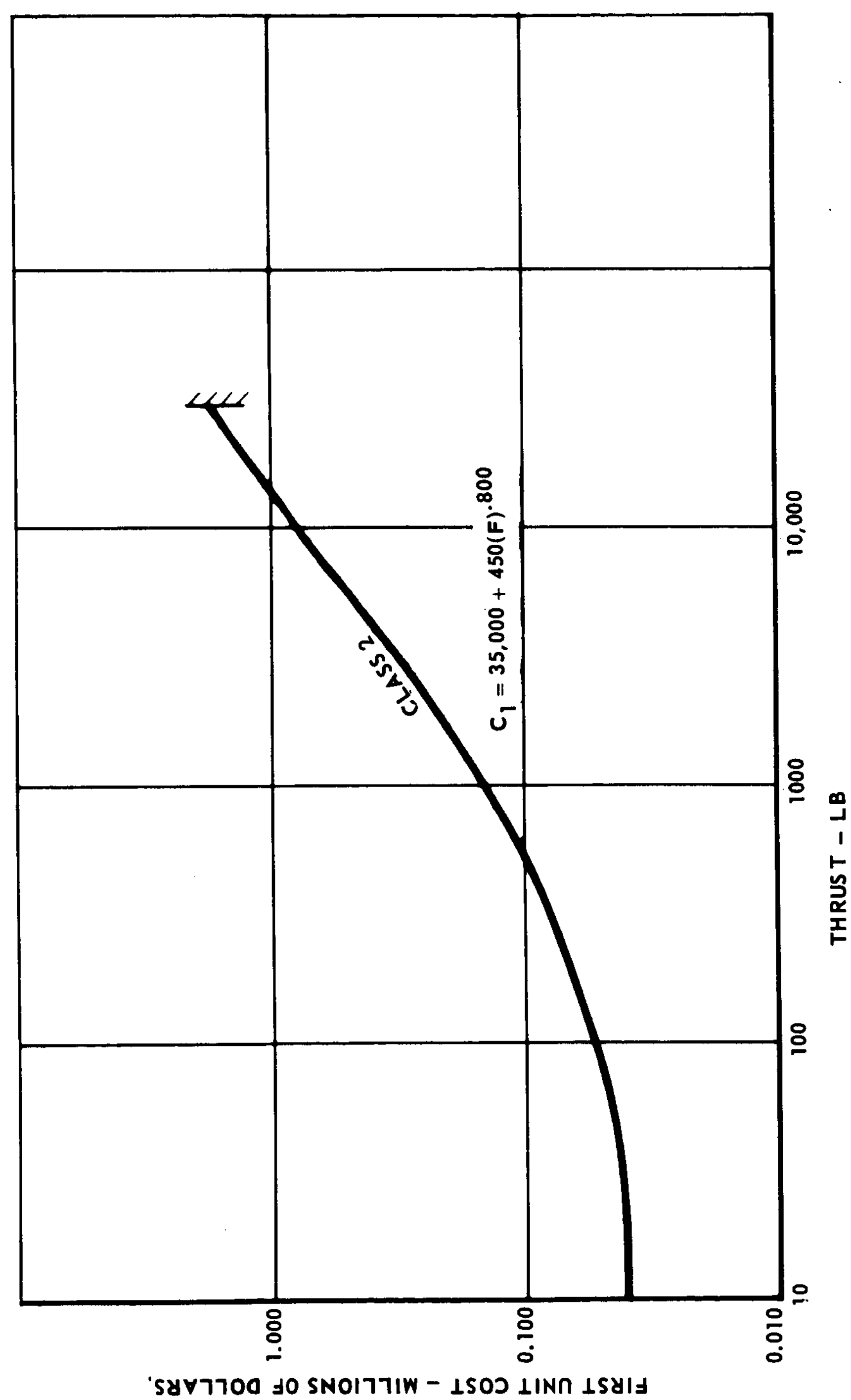
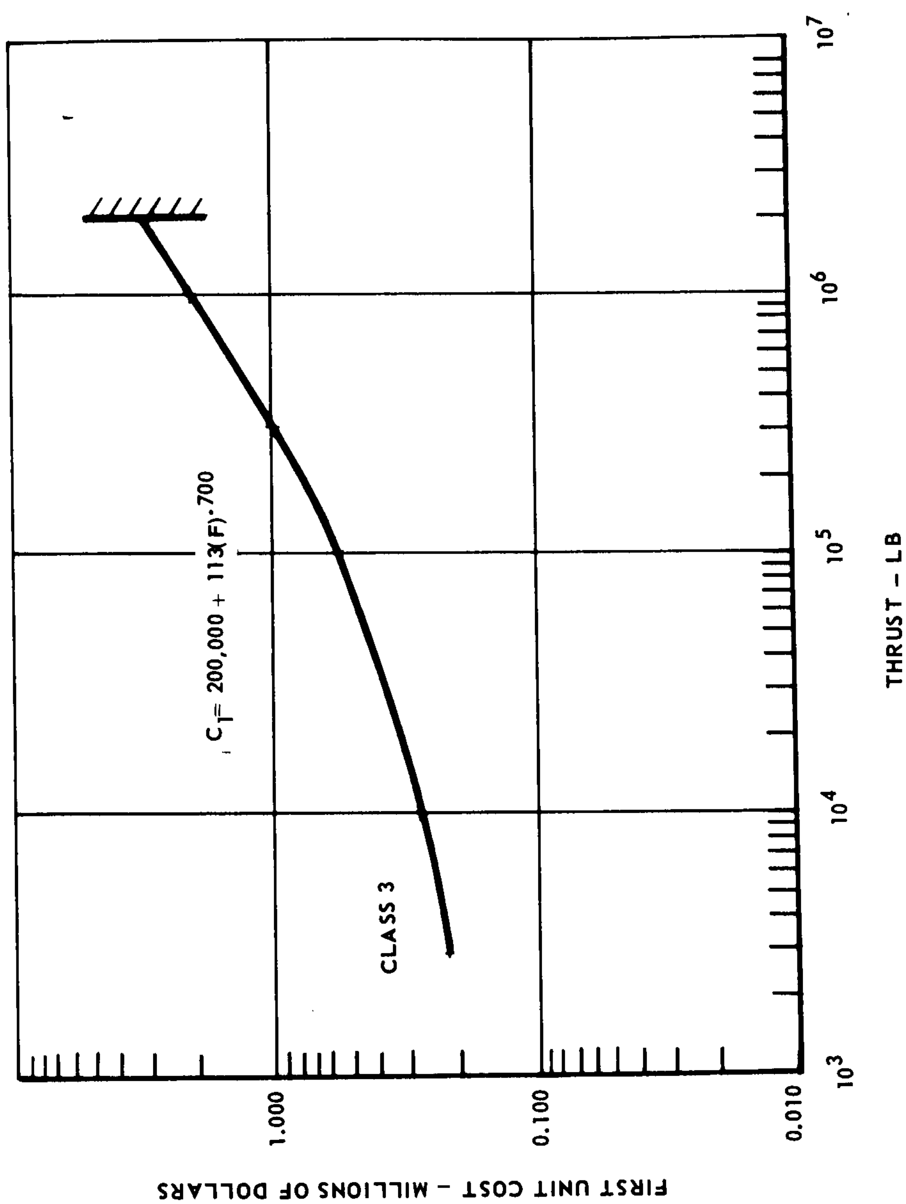


Figure 6–16

PROPULSION – LIQUID ENGINES
REGENERATIVE COOLED, PUMP FED, STORABLE PROPELLANTS (CLASS 3)

FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT



The Class 3 engine CER is shown in Figure 6-16. Eleven data points were available for this engine class. However, some of the data for the relatively old engines is very questionable and for the most part these data points were ignored. The shape of the curve derived for the Class 2 engines was used with the best fit to the data considered to be the most reasonable.

The Class 4 engines are presented in Figure 6-17. The data available includes the RL-10, J-2, and 3 data points provided by Pratt & Whitney. The shape of the curve used here has been influenced by the P&W data, however, the curve drawn is through the RL-10 and J-2 data points.

The CER for small solid rocket motors (SRM) is based on twenty data points and total impulse as the estimating parameter. Although the data presents some scatter, the cost of the SRM's is relatively small and does not warrant further research for CER development. See Figure 6-18. This one CER is used for all the SRM applications in this study.

The propellant tank CER's are presented in Figure 6-19. Tanks that are an integral part of the structure, i.e., load carrying members and the large tanks for the launch upper stage propulsion subsystem are considered part of the structure subsystem. The propulsion subsystem tanks are relatively small tanks separately attached to the main structure. A few large tank data (Thor and S-IVB main) points were included so that the data range could be extended in order to evaluate the effects of such design considerations. The costs are derived as a function of tank volume (V) expressed in cubic feet. No difference in cost between spherical or cylindrical shape tanks was evidenced from the data. A distinction between a tank having and not having a bladder is made. All tanks for the propulsion subsystems, except the launch upper stage, are considered as subcontracted effort. The following CER's were derived.

Bladder Tank, $C_1 = 4.6(10)^4 (V)^{.310}$

Non-Bladder Tank, $C_1 = 3.0(10)^3 (V)^{.623} (KP)$

where

C_1 = First Unit Cost

V = Tank Volume, $Ft.^3$

KP = Type Propellant Factor

= 1.0 for storables

= 1.3 for cryogenics

Figure 6–17

PROPULSION – LIQUID ENGINES
REGENERATIVE COOLED, PUMP FED, CRYOGENIC (LOX/LH_2) PROPELLANTS (CLASS 4)
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT

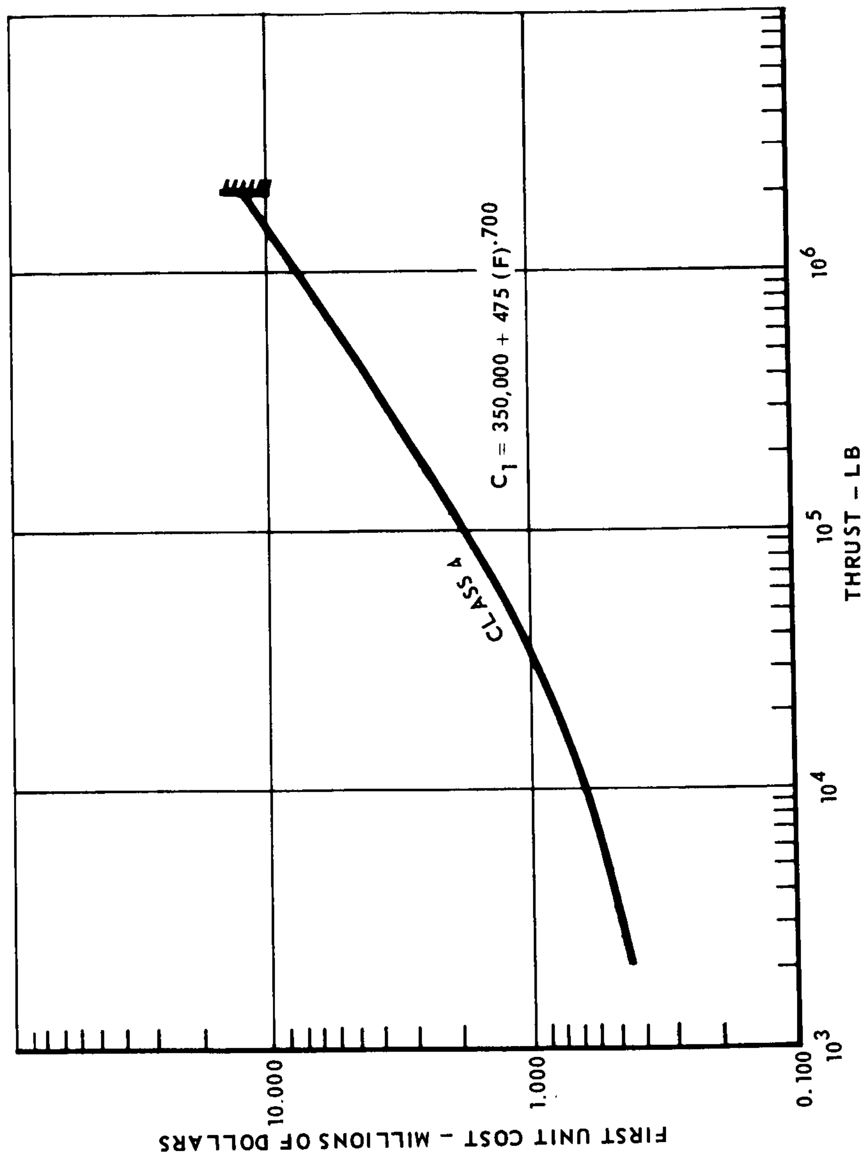


Figure 6-18

PROPULSION – SOLID ROCKET MOTORS
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT

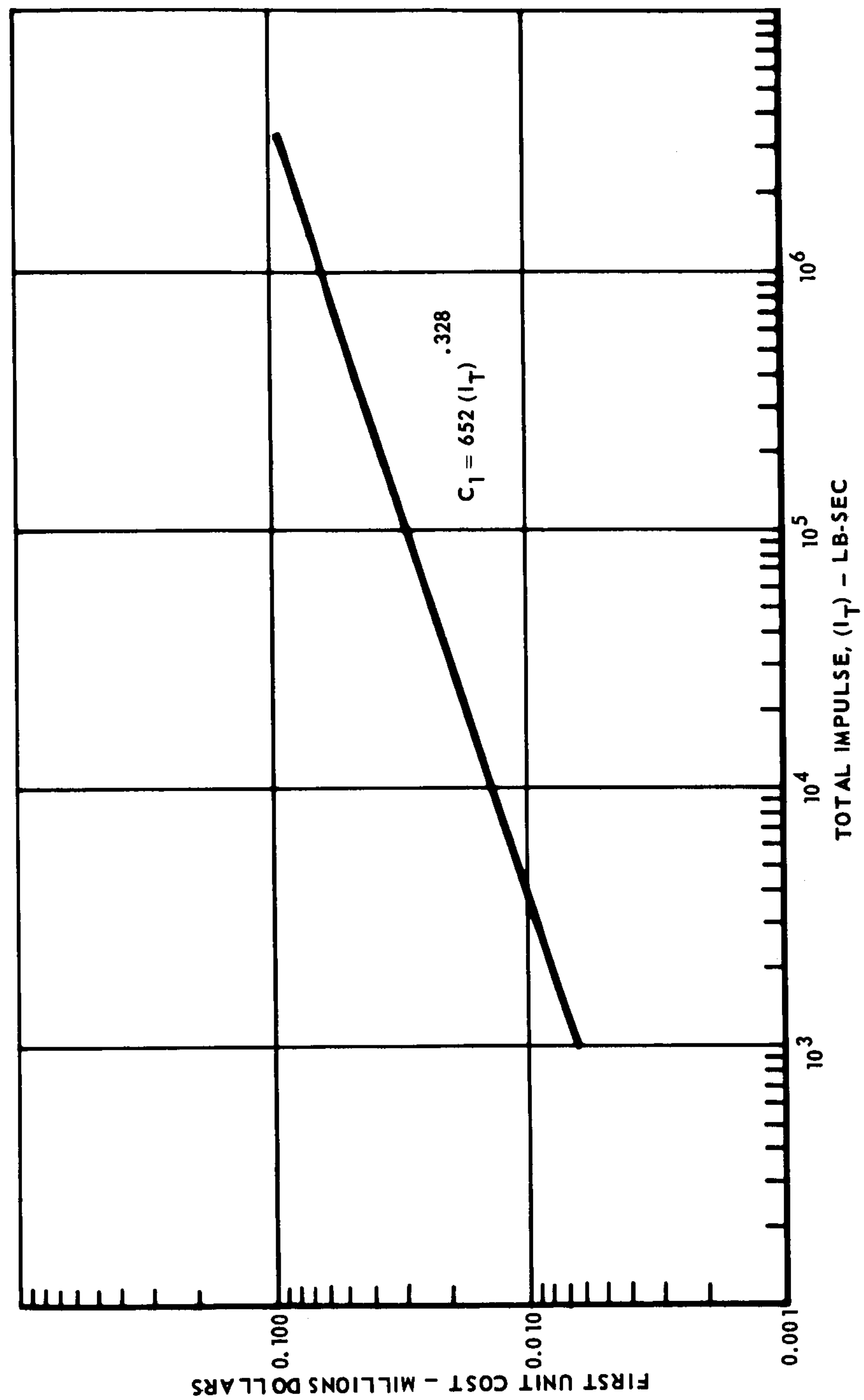
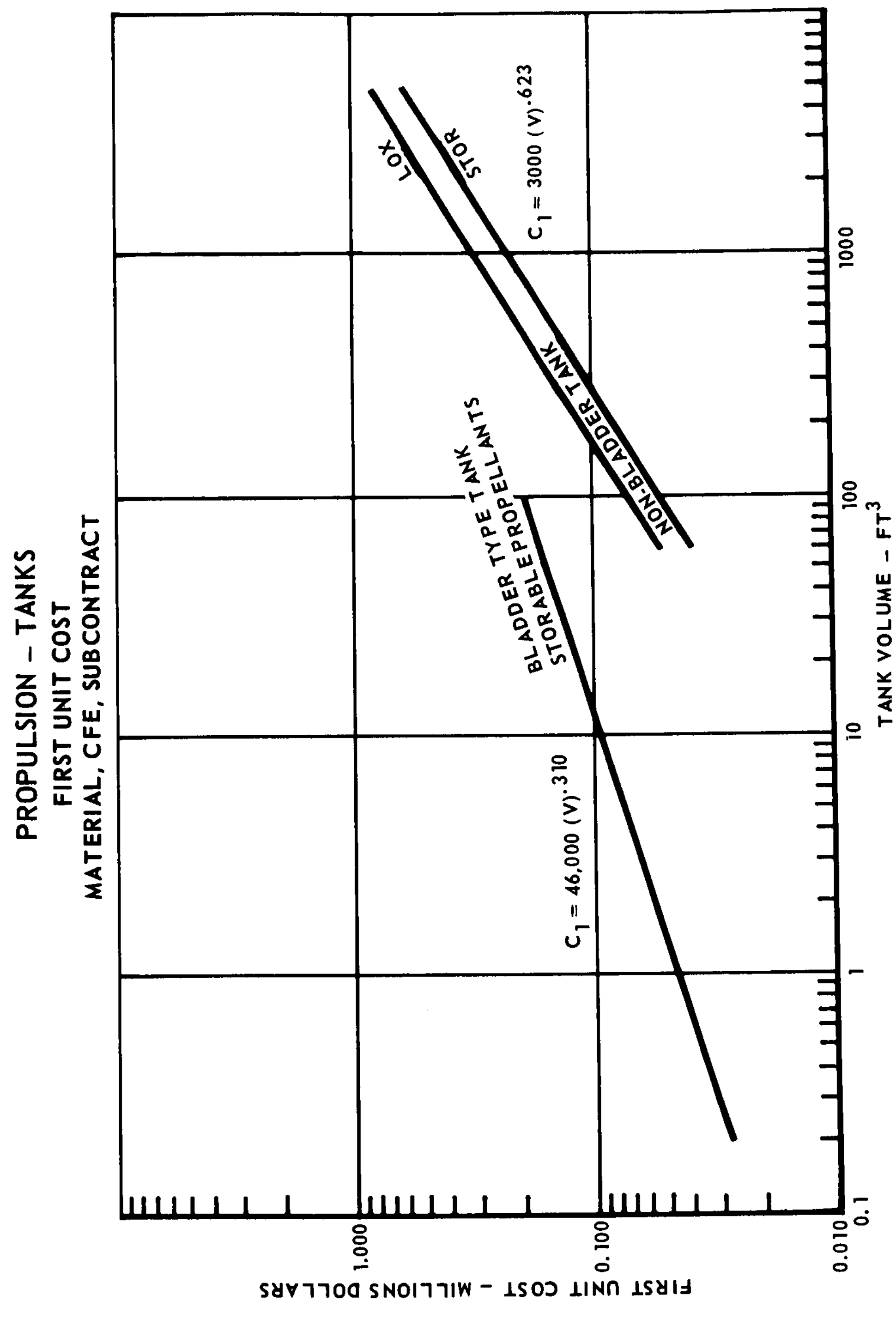


Figure 6–19


PROPULSION – TANKS
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT
LOX
STOR
$C_1 = 3000\ (V)^{.623}$
NON-BLADDER TANK
BLADDER TYPE TANK
STORABLE PROPELLANTS
$C_1 = 46,000\ (V)^{.310}$
0.1
1
10
100
1000
TANK VOLUME – FT^3
0.010
0.100
1.000
FIRST UNIT COST – MILLIONS DOLLARS

The lines, valves, miscellaneous (LVM) category is defined as the propulsion subsystem residue after the engine and tank assemblies are removed. It includes all hardware items that the prime contractor must supply (either fabricate or subcontract) in addition to the engines and propellant tanks in order to constitute a complete functional propulsion subsystem. Similar to the propellant tanks, the LVM category is considered as subcontract effort for the smaller propulsion subsystems and only the launch upper stage subsystem is a prime contractor effort. The data is restricted to two MDAC vehicles, Gemini and the S-IVB stage of the Saturn V launch vehicle. The Gemini data is representative of a subcontracted cost while the S-IVB is indicative of a prime contractor in-house effort. The following CER's were developed for the LVM category.

Subcontract effort (W/O Redundancy)	$C_1 = 59{,}000\ (W)^{.430}$
Subcontract effort (Redundant Sys.)	$C_1 = 89{,}000\ (W)^{.430}$
Launch Upper Stage (Materials cost only)	$C_1 = 5{,}100\ (W)^{.430}$

where

C_1 = First Unit Cost

W = Weight of LVM, lbs.

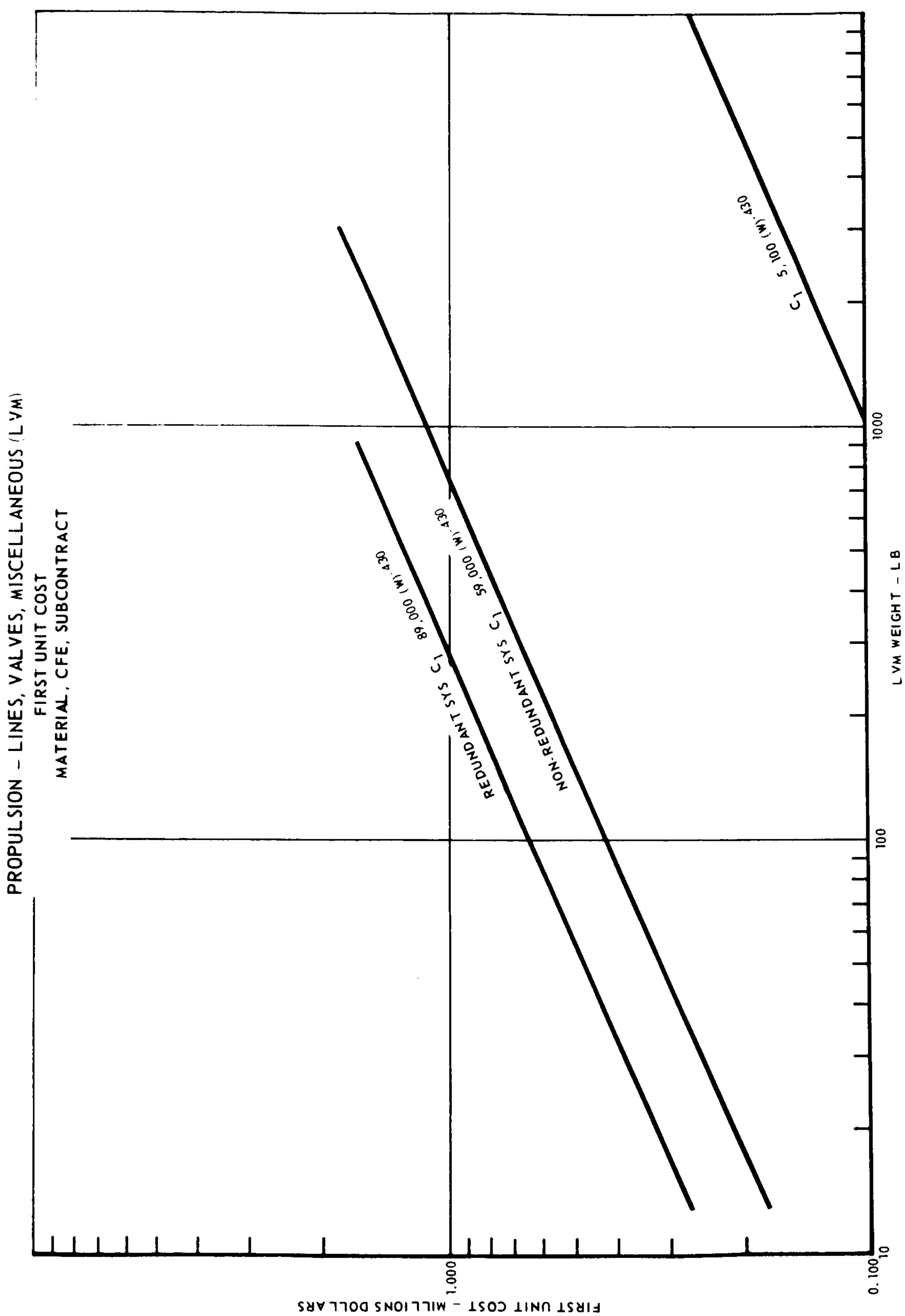
See Figure 6-20 for the plot of the CER's. Three data points, Gemini RCS and OAMS and S-IVB APS, were used for the subcontract case. The Gemini RCS sub system contains a redundant loop for increased reliability, consequently this subsystem's cost and weight were reduced accordingly for comparison to the non-redundant subsystem. The S-IVB cost distribution was modified from prime contractor cost to subcontractor cost in order to be comparable with the Gemini data. Very good correlation of the data was demonstrated.

The S-IVB main subsystem is representative of a prime contractor in-house effort and therefore demonstrates a much lower cost since the cost is only for materials.

6.1.4.11 Final Assembly and Checkout - Miscellaneous materials and equipment are required for the final assembly and acceptance test of the spacecraft. This expenditure has been formulated in terms of the manhours expended for this function.

6.2 Research Development Test and Evaluation Phase (RDT&E) - The RDT&E phase is the design, development, test operations, test hardware, and support effort required for the development and qualification of a system. The CER's developed for the RDT&E phase are presented in this section and will be discussed as nearly as possible by subsystem as outlined by the CES. The CER's are segregated by prime contractor labor and subcontracted costs.

Figure 6–20


PROPULSION – LINES, VALVES, MISCELLANEOUS (LVM)
FIRST UNIT COST
MATERIAL, CFE, SUBCONTRACT
C1 5,100 (W).430
REDUNDANT SYS C1 89,000 (W).430
NON-REDUNDANT SYS C1 59,000 (W).430
LVM WEIGHT – LB
10
100
1000
FIRST UNIT COST – MILLIONS DOLLARS
0.100
1.000

6.2.1 Project Management and Administration - Prime contractor cost of managing the project segments is estimated at 6% of the total RDT&E prime contractor engineering cost as indicated by the Gemini and S-IVB cost history. Miscellaneous materials costs are $1.00 per manhour expended for management and administration.

6.2.2 Thermal/Structure - A very detailed and lengthy analysis was performed for the design and development (D&D) cost of the structural subsystem. As discussed in Section 6.1.3, the type of vehicles represented by the historical programs and the large variations in the configurations to be estimated makes it desirable to separate the structure in major sections. Due to cost data limitations the same segregation employed in the first unit cost category was not possible for the D&D. However, the following segregation was possible.

1. Entry Vehicle Crew Section
2. Entry Vehicle Cargo/Propulsion Section
3. Entry Vehicle - Ablative Thermal Protection
4. Mission Module - Simple Adapter
5. Mission Module - Cargo/Propulsion Section

The entry vehicle crew section houses the crew and most of the mission equipment. It includes all of the E/V structure, the radiative thermal protection system and aerodynamic control surfaces when applicable. The entry vehicle cargo/propulsion section exists only for an integral configuration when the entry vehicle includes the cargo, orbit maneuver propulsion, and/or the main upper stage launch propulsion subsystem. The D&D structural cost includes the basic structure, the radiative thermal protection system and aerodynamic control surfaces when applicable. It was possible to separate the cost of the ablative thermal protection system and therefore it is given as a separate item. The mission module is as described in Section 6.1.3. The landing gear and launch escape tower structure are also segregated as separate subsystems.

The structural D&D cost is further separated into engineering design, test, initial tooling, and materials.

The estimating parameters that were derived from the structural subsystem analysis included the following.

1. Structural Weight
2. Access Area

3. Vehicle Density
4. Temperature Environment
5. Configuration

Structural Weight - Past experience and cost history has shown that structural weight is a good measure of the D&D cost. The variation of engineering design cost with weight is based on in-house detail estimates prepared by the engineering estimating department and actual aircraft cost history. The historical cost and weight data utilized reflects a minimum weight design. A change in philosophy that increases the weight for the same size vehicle (e.g., an increase in the factor of safety in order to reduce testing costs) does not mean that an increase in the cost should be expected. However, the CER as written will show an increase in cost with weight.

Access Area - Access area is the area of the hatches and doors. The access area factor is included in the D&D cost to account for structural complexity evolving from the addition of hatches and doors. The installation of such access hatches and doors significantly increases the D&D manhours required to design the vehicle. This increased effort is due to change in load paths, increased stress and load analysis, increased structural dynamic analysis, increased number of parts to design and analyze, increased number of drawings, and additional tooling requirements.

Vehicle Density - The density factor is included in the structural D&D cost to account for the added complexities arising from high density vehicles. The added effort is due to numerous design problems and changes necessary to finalize the internal structure and equipment arrangements.

Temperature Environment - The temperature factor is included in the structural D&D cost to account for additional thermal analysis required for vehicles exposed to high temperature environments.

Configuration - The above described factors account for the major portion of the "measurable" differences in the vehicles that affect the cost. One additional factor that affects the cost but cannot be quantified by a specific measurable factor is the configuration complexity, usage, or application of the structure. This represents the differences in the complexities of the various vehicles involved; in general it must measure the differences in the number and type of parts and their complexities. An example is the Gemini E/V vs. the S-IVB launch vehicle structure. The number of parts per pound of structure and the complexity of the parts for the Gemini E/V are considerably more than the S-IVB structure. The configuration factor must also account for such things as structural complexity due to the mold line configuration of the vehicle since vehicle shape or configuration directly affects the structure D&D costs. As an example, the D&D cost difference between a high performance fighter aircraft and a ballistic spacecraft is primarily due to internal fuselage propulsion requiring complex inlet air ducts, wings with control surfaces and high lift devices, continuously changing compund curvature mold line, and increased aerodynamic stability and control analysis. A comparison of the expenditures by the aerodynamics department for the F-4 versus the Gemini reveals that the Gemini expenditures were very low in comparison to the F-4. Conversely, a comparison of the thermodynamics department reveals that the Gemini expenditures were much higher. A comparison was made of all the support groups to the basic design project and it was concluded that a lifting body configuration will always be more costly than a ballistic.

The net result is that the vehicles and their cost can only be ranked according to their relative complexities and a factor assigned to each to arrive at a base line from which to estimate. This factor is termed the "Configuration Complexity Factor" and for engineering design is measured by indexing to 1.0 a cylindrical shape configuration such as the S-IVB or the Gemini adapter. The resulting engineering design configuration complexity factors are 1.1 for the ballistic spacecraft, 2.0 for the transport aircraft, and 2.7 for the fighter aircraft. These factors for the historical cost data were then analyzed by comparing the detail cost data and the relative complexities of the vehicles such as outlined in the previous paragraph. It was concluded that the developed factors were reasonable. For the OCPDM study we are concerned with two basic configurations: 1. Ballistic, 2. Lifting Body. The "Configuration Complexity Factor" for the ballistic is of course the same as the Gemini and Mercury factor and therefore requires no interpretation to arrive at the value. However the factor for the lifting body, or more specifically the M2-F2, must be estimated.

The configuration complexity factor for the lifting body spacecraft was developed from an analysis of aircraft history. The aircraft configuration factor was divided between the wing and the fuselage and then used to estimate the M2-F2 factor. The total factor is derived based on the percentage distribution of cost between the wing and fuselage and the corresponding factors as outlined by the following:

	WING %	WING FACTOR	FUSELAGE %	FUSELAGE FACTOR	TOTAL FACTOR
Fighter Aircraft	40	2.2	60	3.1	2.7
Transport Aircraft	66	2.2	34	1.7	2.0
M2-F2 Spacecraft	25	2.0	75	1.9	1.9

It is to be noted that the configuration factor is an estimated value and is a matter of estimating judgement based on the relative complexities of the vehicles involved. The M2-F2 wing factor is slightly less than the aircraft factor since the M2-F2 does not have the large number of flaps, ailerons, speed brakes, spoilers, and high lift devices that are a part of the aircraft wing. The M2-F2 fuselage factor was estimated to be slightly more than the transport aircraft and considerably less than the fighter aircraft since the M2-F2 is similar in complexity to the transport aircraft and does not have the internal propulsion, complex inlet ducts, etc. that are a part of the fighter aircraft. Figure 6-21 displays the configuration complexity factors developed for engineering design.

Each of the above discussed parameters has a different affect on the cost categories to be estimated. An example is the access area parameter for engineering design versus initial tooling. The effect on tooling is much greater because the tooling cost includes both design and fabrication of the tooling. Additionally tooling cost is increased more because the number of tools is increased along with increased tolerance requirements. Some of the CER's exclude one or more of the above parameters if the parameter is not pertinent to the structural section to be estimated.

6.2.2.1 Engineering Design - The following CER's have been developed for structure engineering design.

I Entry Vehicle Engineering Design Cost

Crew Section = $3510(\mathrm{WSCSET})^{.485}(\mathrm{KACSE})(\mathrm{KCCS})(\mathrm{KDCS})(\mathrm{KENGR})$

Cargo/Propulsion Section = $3510(\mathrm{WSCPET})^{.485}(\mathrm{KACPE})(\mathrm{KCCP})(\mathrm{KDCP})(\mathrm{KENGR})$

Launch Escape Tower Structure = $535(\mathrm{WSLET})^{.485}(\mathrm{KENGR})$

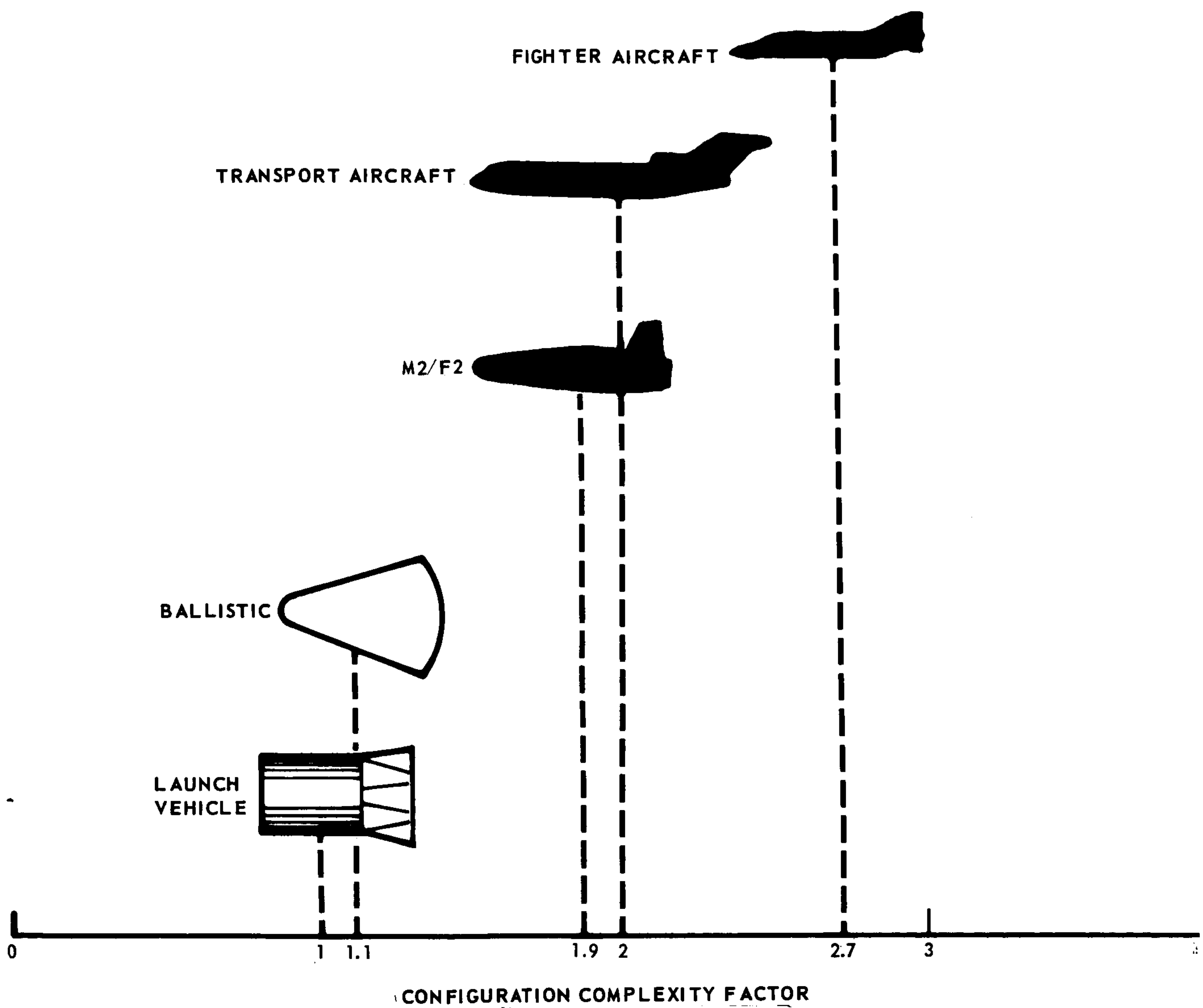
Launch Upper Stage Propellant Tanks = $2440(\mathrm{WT})^{.485}(\mathrm{KENGR})$

II Mission Module Engineering Design Cost

Simple Adapter = $760(\mathrm{WSA})^{.485}(\mathrm{KENGR})$

Figure 6-21

CONFIGURATION COMPLEXITY FACTOR
ENGINEERING DESIGN



Cargo/Propulsion Section = $3050(WSCPM)^{.485}(KACPME)(KDCPM)(KENGR)$

Where

WSXXX = Structural Weight of the Section, Lbs.

WT = Total Dry Weight of a Tank, Lbs.

KAXXX = Access Area Factor of the Section

$= 2\left(\frac{\text{Area Hatches \& Doors}}{\text{Total Wetted Area}}\right) + 1$

KDXXX = Density Factor of the Section

$= \left[\frac{\text{Total Empty Wt. (Dry), Lbs.}}{\text{Total Mold Line Volume, Ft}^3}\right]^{.25}$

KC XXX = Configuration Factor of the Section, See Figure 6-21.

= 1.1 for ballistic entry vehicle

= 1.9 for M_2/F2 entry vehicle

KENGR = Engineering Labor Rate

The temperature factor has been incorporated into the constant in each equation since it is fixed for entry structure at 1.15 & 1.0 for non-entry structure. See Figure 6-22 for a plot of the CER's.

The landing gear CER's are based solely on the F-4 aircraft and landing gear weight. See Figure 6-23.

The CER for the ablative thermal protection system (TPS) is based on Gemini cost history. The estimating parameters are average individual panel size and total area of the ablative TPS. The exponents derived are estimated values since no actual cost history is available for this subsystem. See Figure 6-24.

6.2.2.2 Engineering Test - The following CER's have been developed for structure engineering test.

I Entry Vehicle Engineering Test Cost

Crew Section = $1040(WSCSET)^{.766}(KENGR)$

Cargo/Propulsion Section = $830(WSCPET)^{.766}(KENGR)$

Launch Escape Tower Structure = $130(WSLET)^{.766}(KENGR)$

Launch Upper Stage Propellant Tanks = $531(WT)^{.766}(KENGR)$

II Mission Module Engineering Test Cost

Figure 6-22

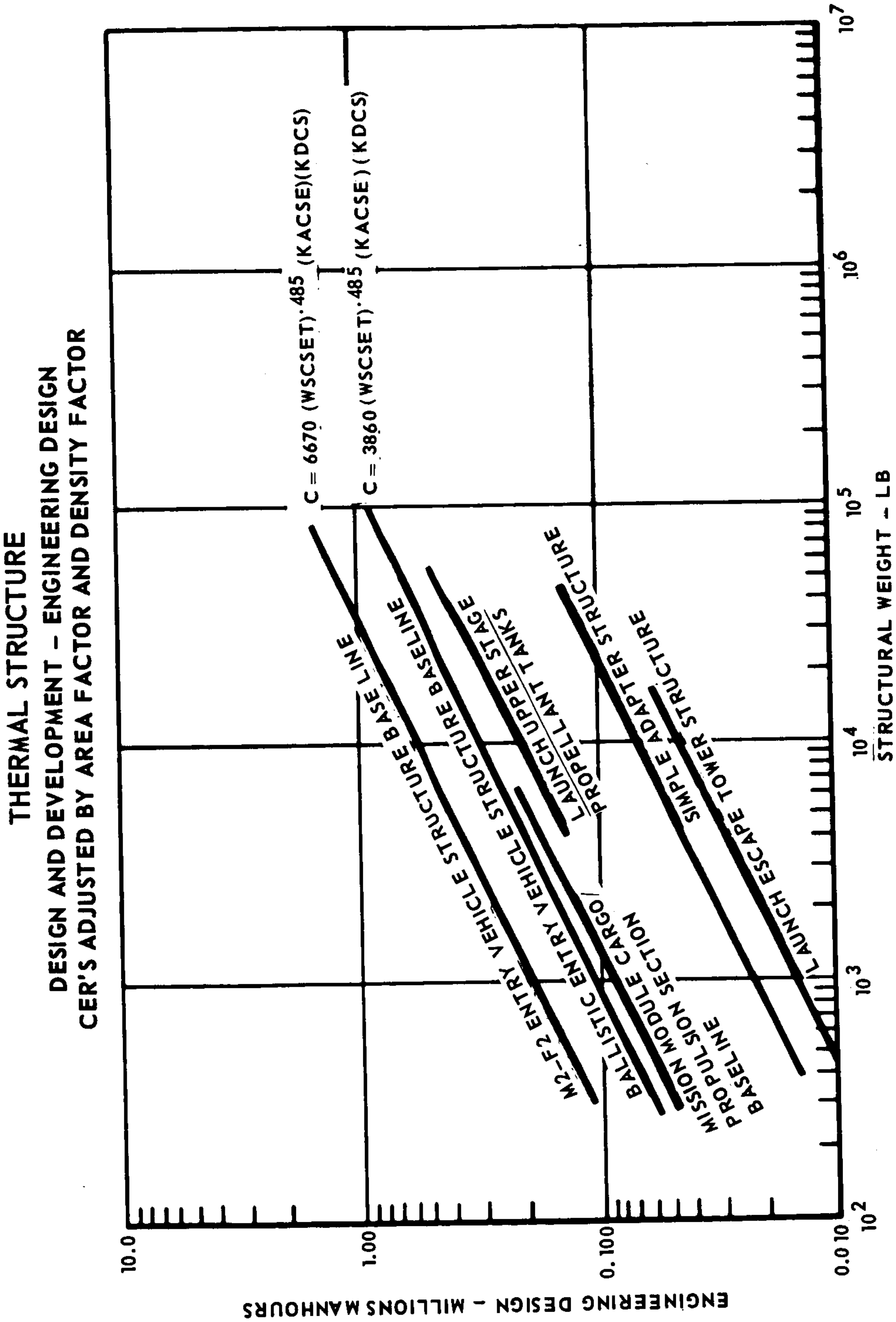

THERMAL STRUCTURE
DESIGN AND DEVELOPMENT – ENGINEERING DESIGN
CER'S ADJUSTED BY AREA FACTOR AND DENSITY FACTOR
C = 6670 (WSCSET)$^{.485}$ (KACSE)(KDCS)
C = 3860 (WSCSET)$^{.485}$ (KACSE)(KDCS)
BASE LINE
M2–F2 ENTRY VEHICLE STRUCTURE BASELINE
ENTRY VEHICLE STRUCTURE BASELINE
LAUNCH VEHICLE UPPER STAGE
BALLISTIC CARGO/
PROPELLANT TANKS
MODULE SECTION
MISSION
PROPULSION
BASELINE
LAUNCH STRUCTURE
SIMPLE ADAPTER STRUCTURE
LAUNCH ESCAPE TOWER STRUCTURE
10.0
1.00
0.100
0.010
ENGINEERING DESIGN – MILLIONS MANHOURS
10^2
10^3
10^4
10^5
10^6
10^7
STRUCTURAL WEIGHT – LB

Figure 6-23

THERMAL/STRUCTURE – LANDING GEAR
DESIGN AND DEVELOPMENT
ENGINEERING DESIGN AND TEST

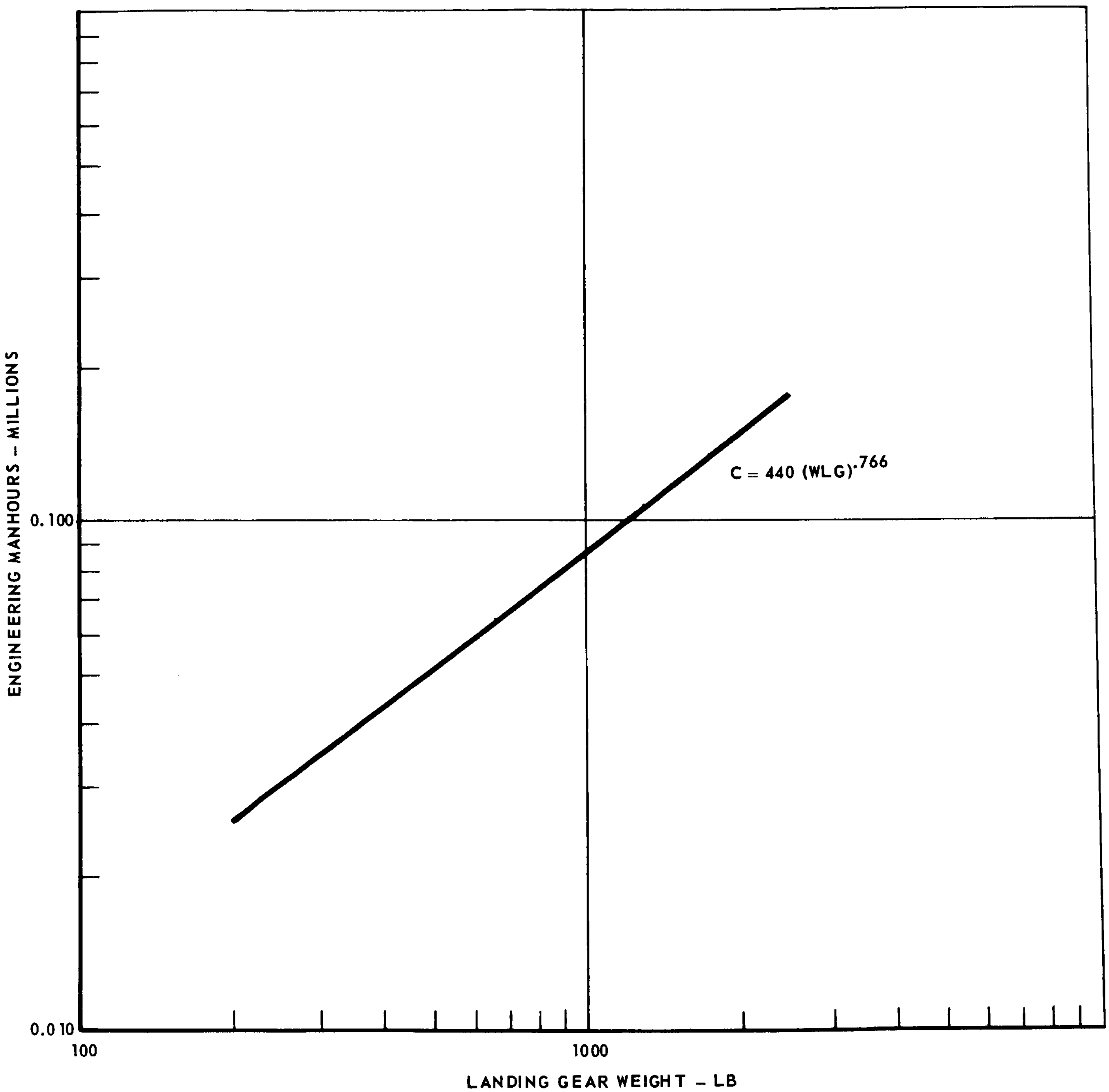


Figure 6–24

THERMAL/STRUCTURE – ABLATIVE THERMAL PROTECTION
DESIGN AND DEVELOPMENT
ENGINEERING DESIGN AND TEST

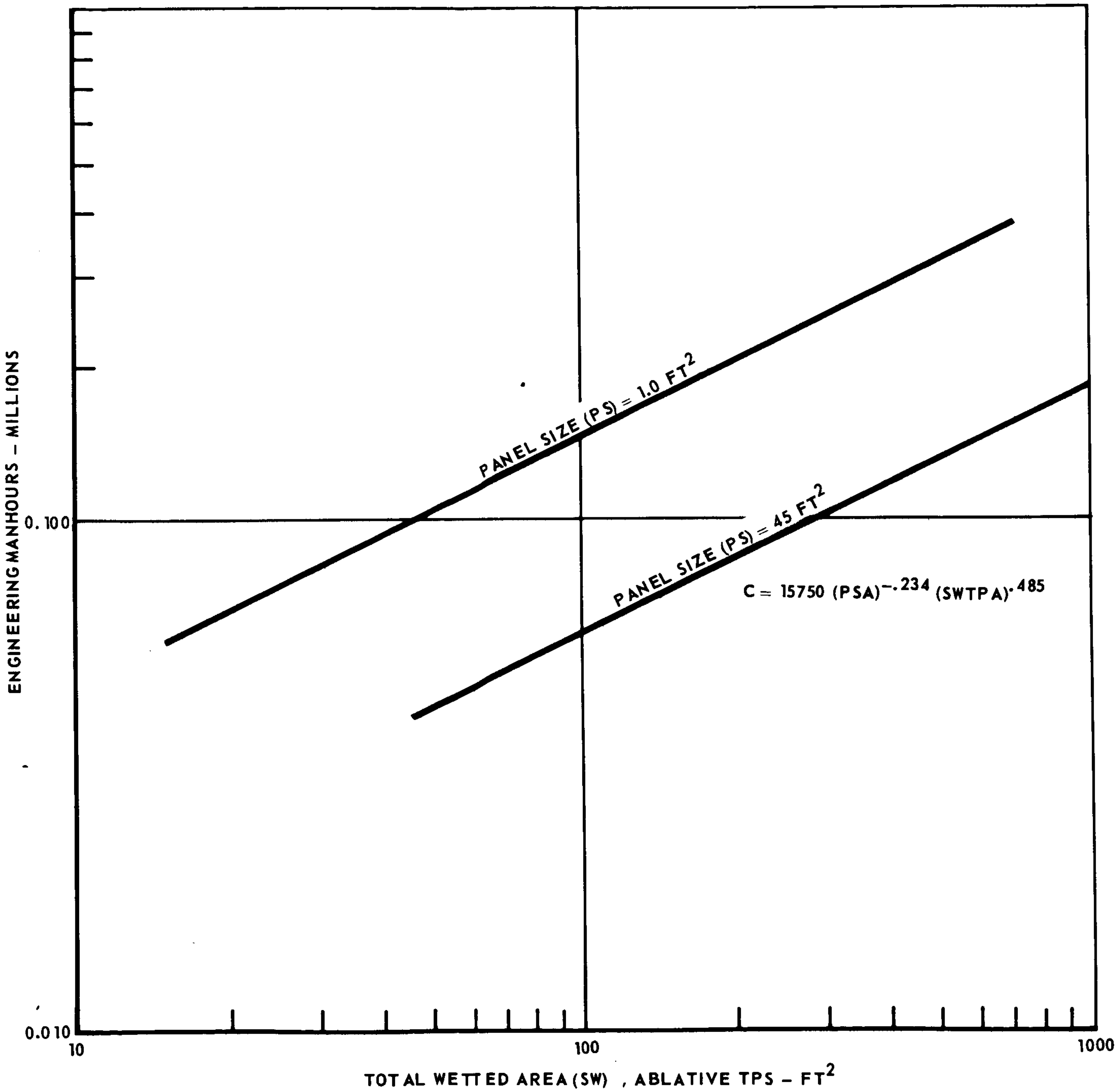
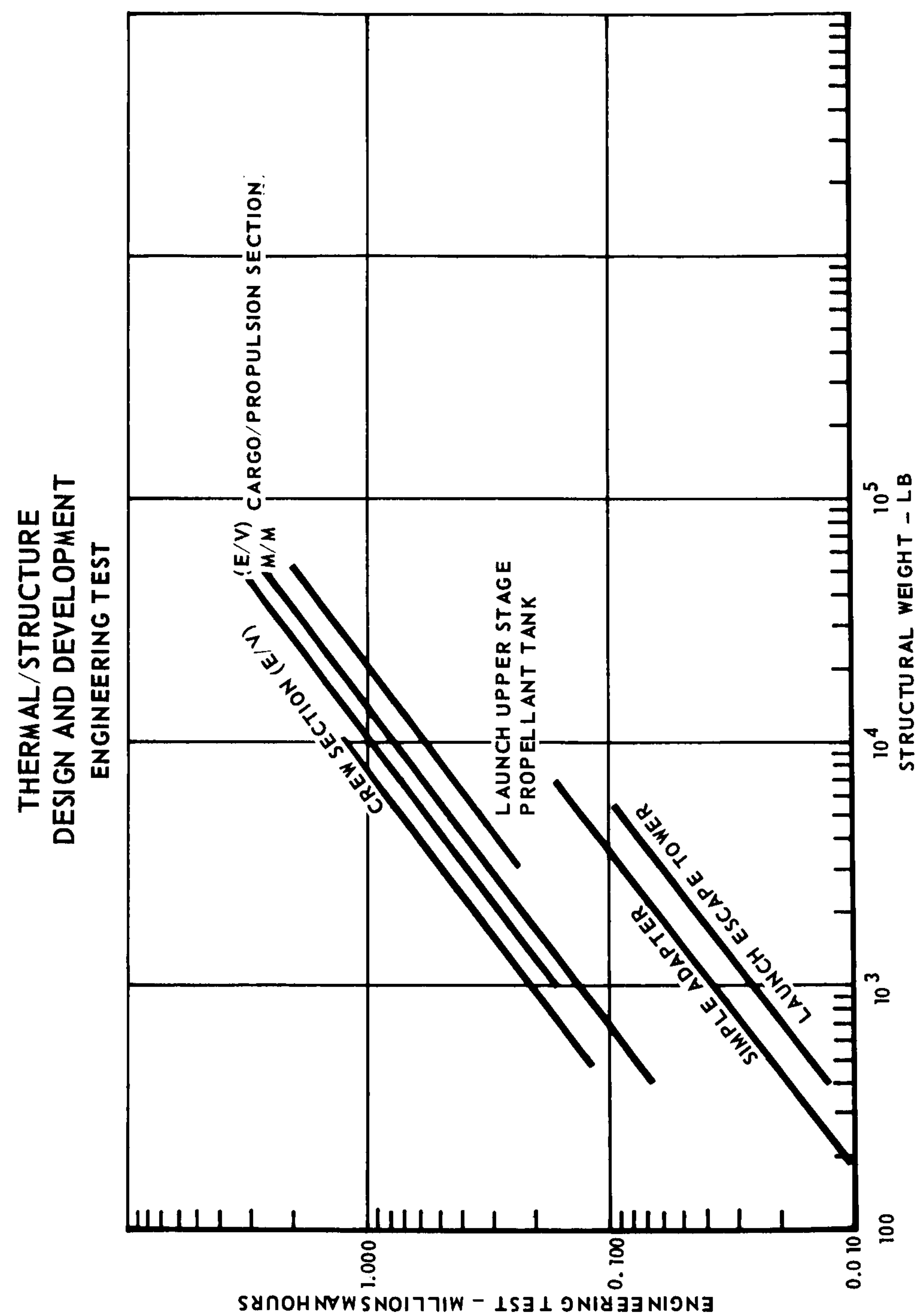


Figure 6–25


THERMAL/STRUCTURE
DESIGN AND DEVELOPMENT
ENGINEERING TEST
CARGO/PROPULSION SECTION
(E/V)
M/M
CREW SECTION (E/V)
LAUNCH UPPER STAGE
PROPELLANT TANK
LAUNCH ESCAPE TOWER
SIMPLE ADAPTER
100
10^3
10^4
10^5
STRUCTURAL WEIGHT – LB
0.010
0.100
1.000
ENGINEERING TEST – MILLIONS MAN HOURS

Simple Adapter = $187(WSA)^{.766}(KENGR)$

Cargo/Propulsion Section = $664(WSCPM)^{.766}(KENGR)$

Where

WSXXX = Structural Weight of the Section, Lbs.

WT = Total Dry Weight of a Tank, Lbs.

KENGR = Engineering Labor Rate

See Figure 6-25 for a plot of the CER's. The entry vehicle cargo/propulsion section was estimated to be 25 percent greater than the mission module cargo/propulsion section to account for elevated temperature testing.

6.2.2.3 Initial Tooling - Initial tooling includes the design and fabrication of the tooling required by the prime contractor. Cost data adjustments similar to those described in Section 6.1.2 Sustaining Tooling were required. Figure 6-26 presents the basic CER's as adjusted by the area factor. The configuration developed for the tooling CER uses the ballistic entry vehicle as a base of 1.0. The configuration factor for the M2/F2 was estimated to be 1.5. The entry vehicle cargo/propulsion section was estimated to be 0.80 of the E/V crew section. When compared to the mission module cargo/propulsion section this estimate does not seem unrealistic.

The following CER's have been developed:

I Entry Vehicle Initial Tooling Cost

Crew Section = $880(WSCSET)^{.766}(KACST)(KCT)KTOOL)$

Cargo/Propulsion Section = $700(WSCPET)^{.766}(KACPT)(KTOOL)(KCT)$

Launch Escape Tower Structure = $130(WSLET)^{.766}(KTOOL)$

Launch Upper Stage Propellant Tanks = $610(WT)^{.766}(KTOOL)$

II Mission Module Initial Tooling Cost

Simple Adapter = $186(WSA)^{.766}(KTOOL)$

Cargo/Propulsion Section = $480(WSCPM)^{.766}(KACPMT)\ (KTOOL)$

Where

WSXXX = Structural Weight of the Section, Lbs.

WT = Total Dry Weight of a Tank, Lbs.

KAXXX = Access Area Factor of the Section.

Figure 6-26

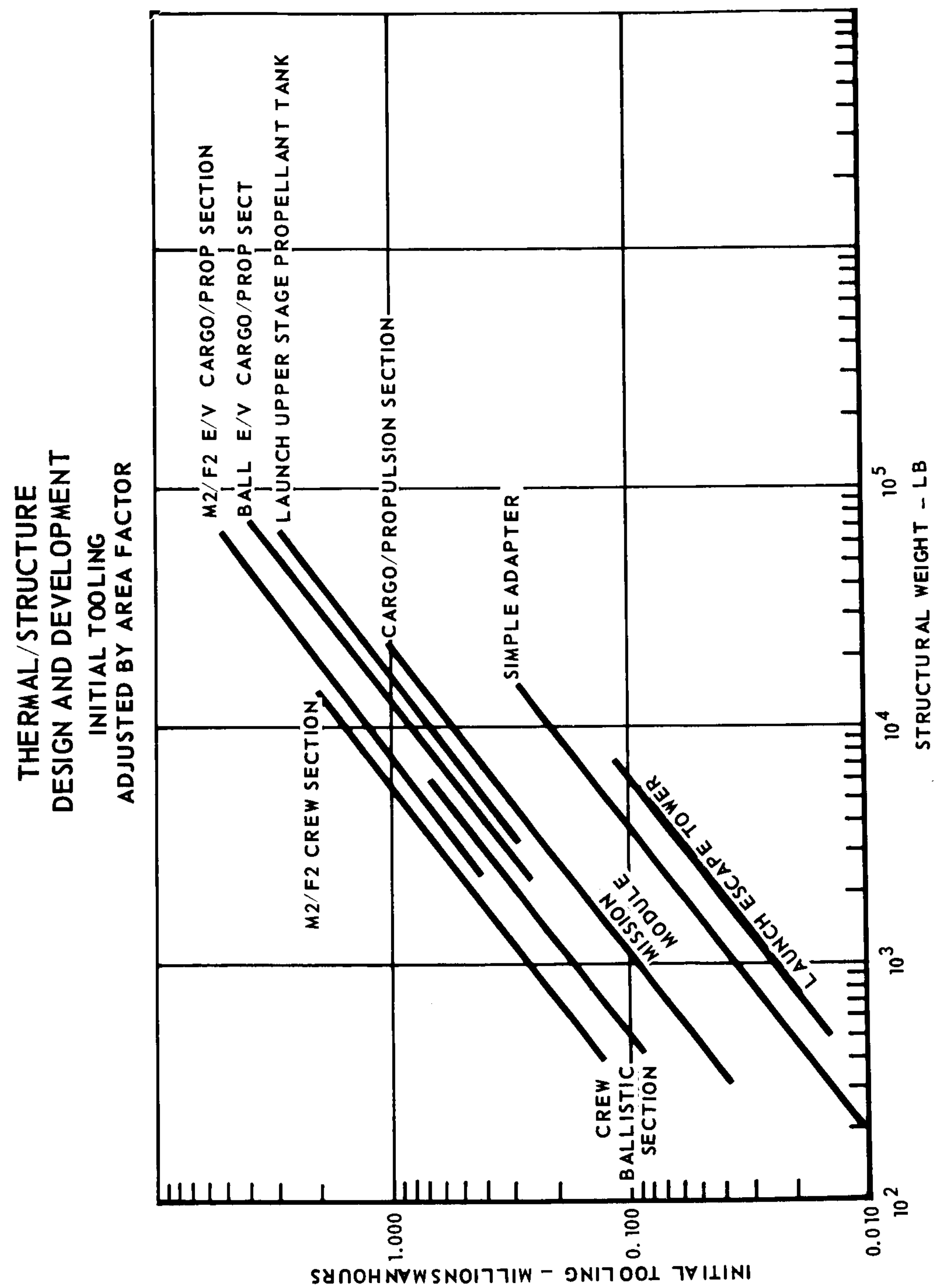
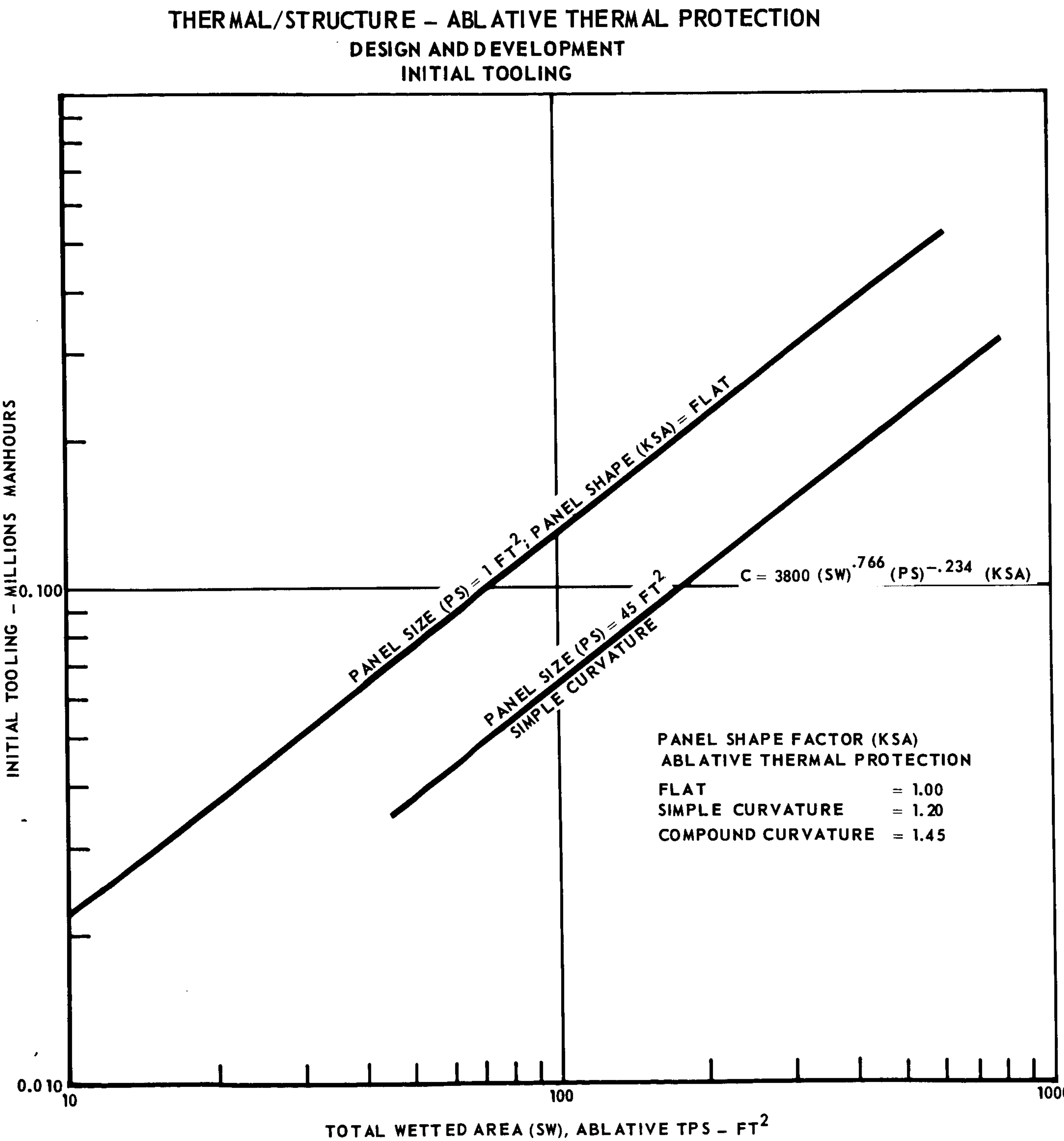

THERMAL/STRUCTURE
DESIGN AND DEVELOPMENT
INITIAL TOOLING
ADJUSTED BY AREA FACTOR
M2/F2 E/V CARGO/PROP SECTION
BALL E/V CARGO/PROP SECT
LAUNCH UPPER STAGE PROPELLANT TANK
CARGO/PROPULSION SECTION
SIMPLE ADAPTER
M2/F2 CREW SECTION
LAUNCH ESCAPE TOWER
MISSION MODULE
CREW
BALLISTIC
SECTION
1.000
0.100
0.010
10^2
10^3
10^4
10^5
STRUCTURAL WEIGHT - LB
INITIAL TOOLING - MILLIONSMANHOURS

Figure 6-27


THERMAL/STRUCTURE – ABLATIVE THERMAL PROTECTION
DESIGN AND DEVELOPMENT
INITIAL TOOLING
INITIAL TOOLING – MILLIONS MANHOURS
0.100
0.010
10
100
1000
TOTAL WETTED AREA (SW), ABLATIVE TPS – FT2
PANEL SIZE (PS) = 1 FT2; PANEL SHAPE (KSA) = FLAT
PANEL SIZE (PS) = 45 FT2
SIMPLE CURVATURE
C = 3800 (SW).766 (PS)-.234 (KSA)
PANEL SHAPE FACTOR (KSA)
ABLATIVE THERMAL PROTECTION
FLAT = 1.00
SIMPLE CURVATURE = 1.20
COMPOUND CURVATURE = 1.45

$$= 7 \left(\frac{\text{Area Hatches \& Doors}}{\text{Total Wetted Area}}\right) + 1$$

KTOOL = Tooling Labor Rate

KCT = Configuration Factor; Ballistic = 1.0; M2-F2 = 1.5

The CER for the ablative thermal protection system (TPS) is based on Gemini cost history. The estimating parameters are average individual panel size, total wetted area of the ablative TPS, and a complexity factor for panel shape. The exponents derived are estimated values since no actual cost history is available. See Figure 6-27.

Tooling cost for the landing gear is based on the F-4 aircraft. See Figure 6-28.

6.2.3 Prime Contractor Engineering - The prime contractor's engineering cost for the subcontracted subsystems can be estimated as a function of the subcontractor's expenditures. Figure 6-29 presents the CER's that have been derived from the Gemini and Mercury cost history.

6.2.4 Inflatable Aerodynamic Devices - The prime contractor engineering CER for the subsystem is discussed in Paragraph 6.2.3. The CER for the subcontract cost of the parachute is based on Gemini cost history; the sailwing is estimated at 1.5 times the parachute. See Figure 6-30.

6.2.5 Power Supply and Ordnance - This group consists of several subsystems as discussed in the following paragraphs.

6.2.5.1 Electrical Distribution - The prime contractor engineering cost (CER) was based on Gemini cost history with the differential between entry vehicle and mission module as indicated by the cost data. See Figure 6-31. The subcontract cost CER was also based on Gemini. This cost category includes vendor cost for design and qualification of minor electrical parts. The cost history was not separable between entry and mission module and therefore the same CER is used for both. See Figure 6-32.

6.2.5.2 Fuel Cell - The prime contractor engineering CER for this subsystem is discussed in Paragraph 6.2.3. The subcontract CER is an estimated value with power level and number of fuel cells as the estimating parameters. The Gemini cost history is not considered applicable because it represents an advancement in the state of the art. The cost data supplied by Allis Chalmers was for an existing 2 KW cell. See Figure 6-33.

6.2.5.3 Batteries - The prime contractor engineering CER is based on an estimate with battery weight as the estimating parameter. See Figure 6-34. The

Figure 6–28

THERMAL/STRUCTURE – LANDING GEAR
DESIGN AND DEVELOPMENT
INITIAL TOOLING

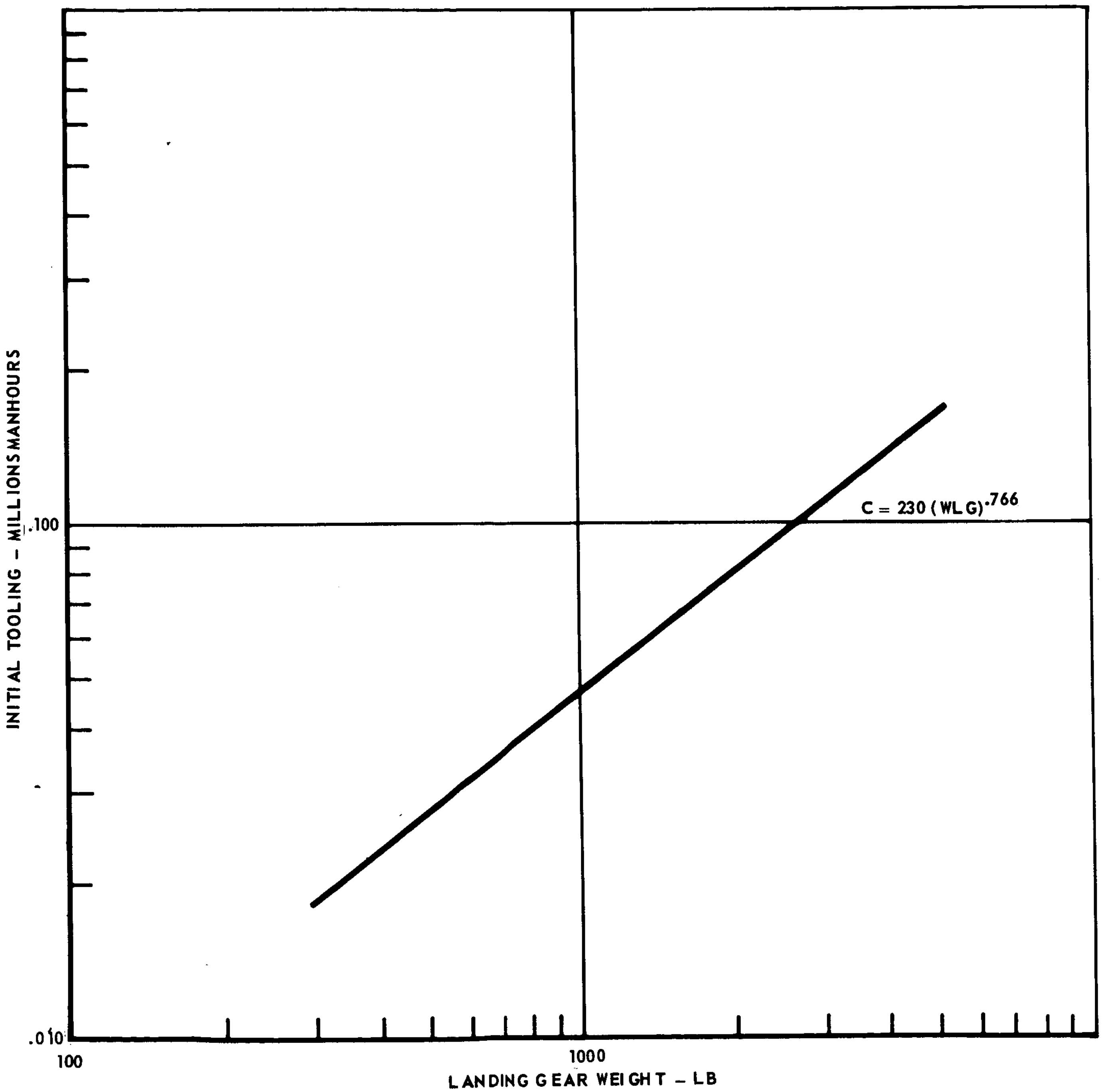


Figure 6–29

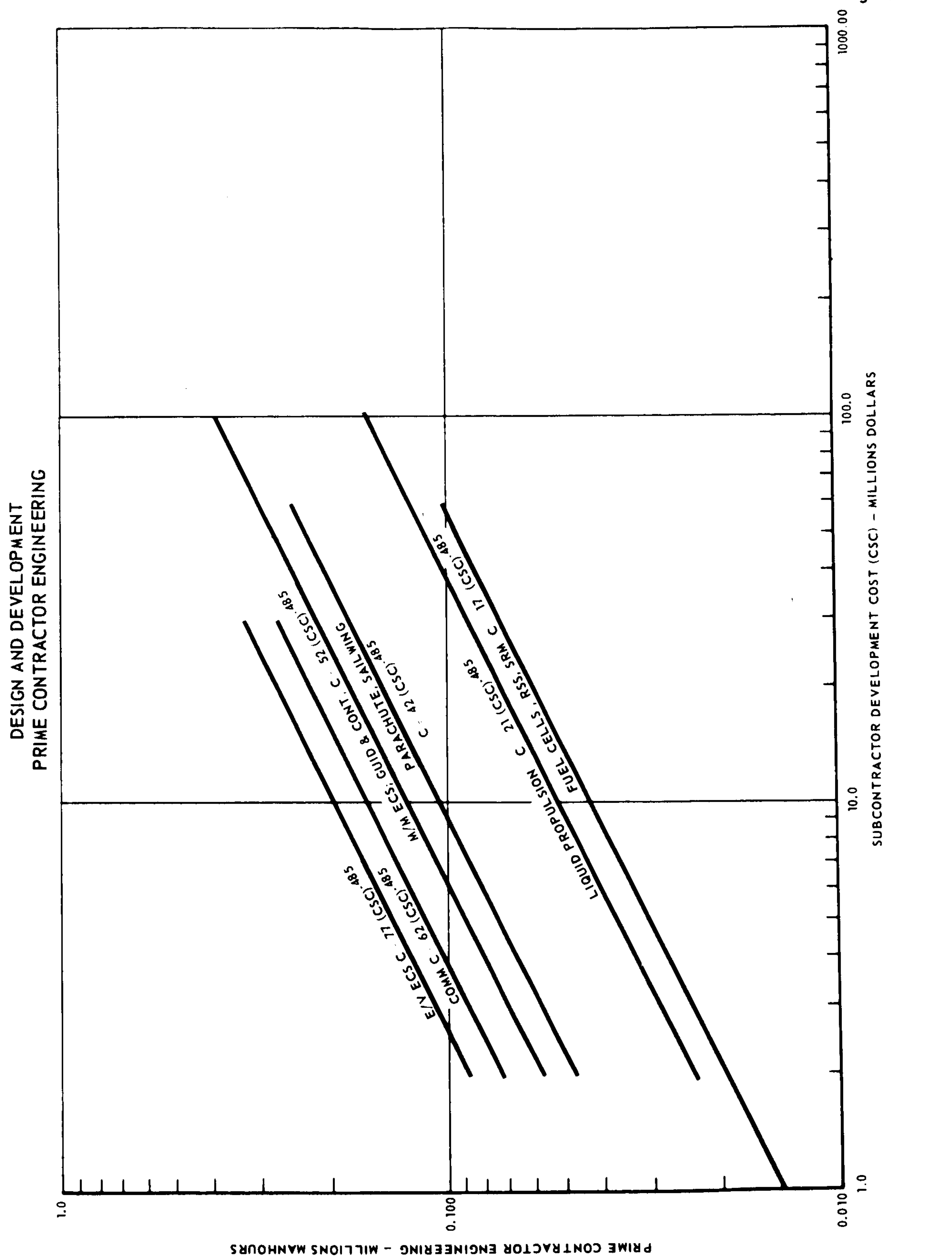

DESIGN AND DEVELOPMENT
PRIME CONTRACTOR ENGINEERING
E/V ECS C = 77 (CSC)^.485
COMM C = 62 (CSC)^.485
M/M ECS; GUID & CONT. C = 52 (CSC)^.485
PARACHUTE, SAILWING C = 42 (CSC)^.485
LIQUID PROPULSION C = 21 (CSC)^.485
FUEL CELLS, RSS, SRM C = 17 (CSC)^.485
1.0
0.100
0.010
PRIME CONTRACTOR ENGINEERING – MILLIONS MANHOURS
1.0
10.0
100.0
1000.00
SUBCONTRACTOR DEVELOPMENT COST (CSC) – MILLIONS DOLLARS

Figure 6-30

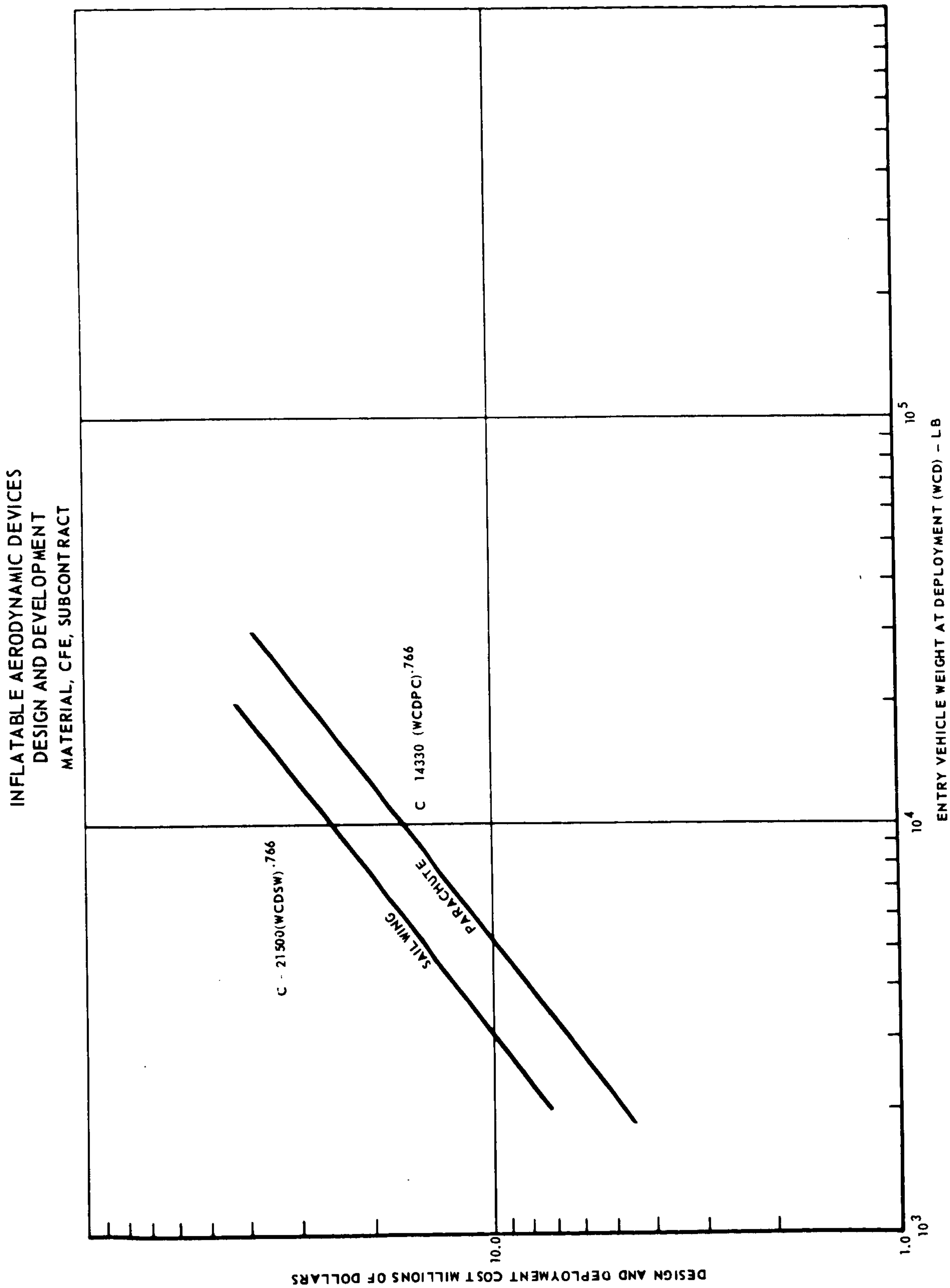

INFLATABLE AERODYNAMIC DEVICES
DESIGN AND DEVELOPMENT
MATERIAL, CFE, SUBCONTRACT
C 14330 (WCDPC).766
C - 21500(WCDSW).766
PARACHUTE
SAIL WING
ENTRY VEHICLE WEIGHT AT DEPLOYMENT (WCD) - LB
10^3
10^4
10^5
DESIGN AND DEPLOYMENT COST MILLIONS OF DOLLARS
1.0
10.0

Figure 6-31

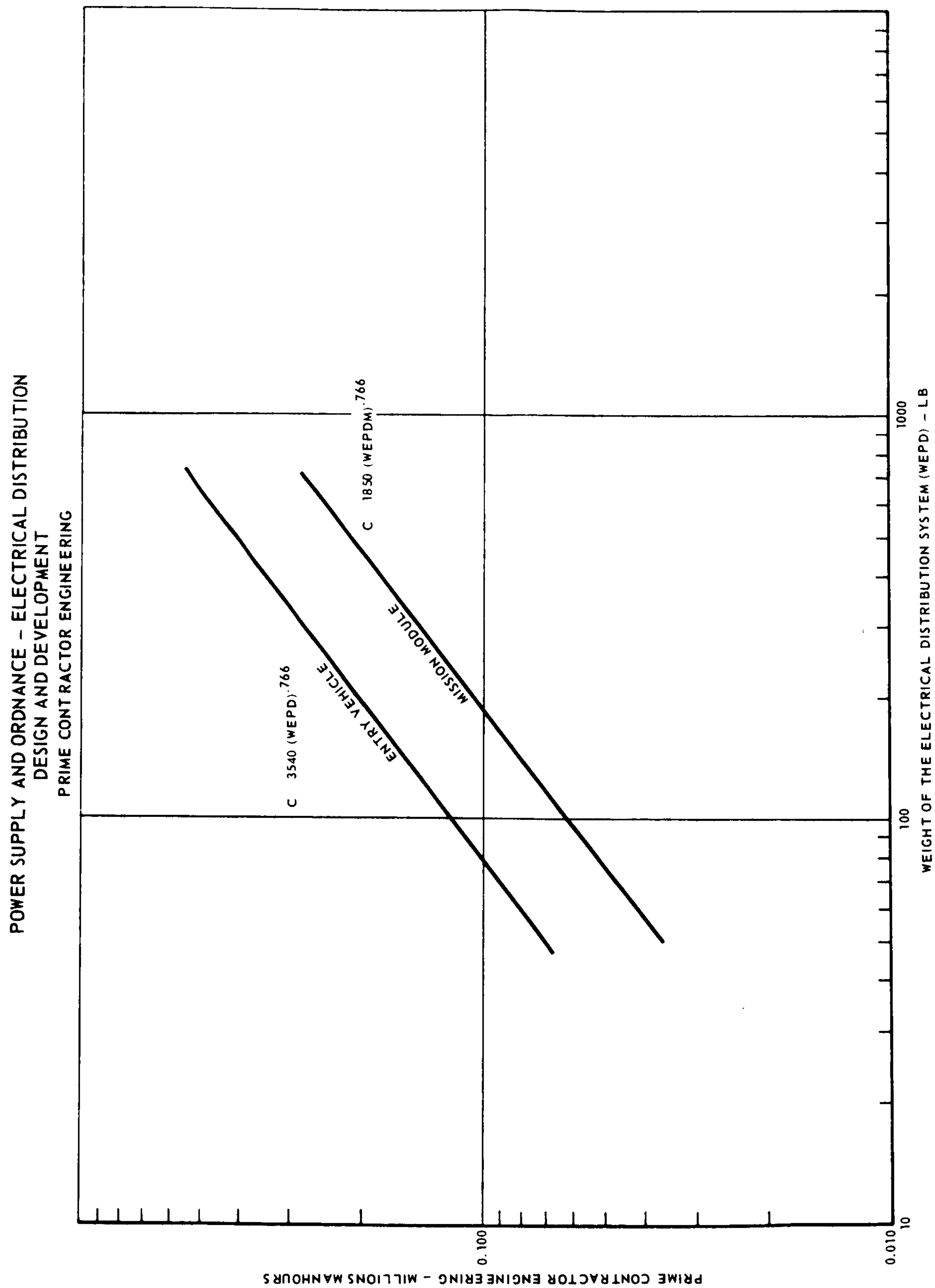

POWER SUPPLY AND ORDNANCE – ELECTRICAL DISTRIBUTION
DESIGN AND DEVELOPMENT
PRIME CONTRACTOR ENGINEERING
C 3540 (WEPD)^.766
ENTRY VEHICLE
C 1850 (WEPDM)^.766
MISSION MODULE
10
100
1000
WEIGHT OF THE ELECTRICAL DISTRIBUTION SYSTEM (WEPD) – LB
0.010
0.100
PRIME CONTRACTOR ENGINEERING – MILLIONS MANHOURS

Figure 6-32

POWER SUPPLY AND ORDNANCE – ELECTRICAL DISTRIBUTION
DESIGN AND DEVELOPMENT
MATERIAL, CFE, SUBCONTRACT

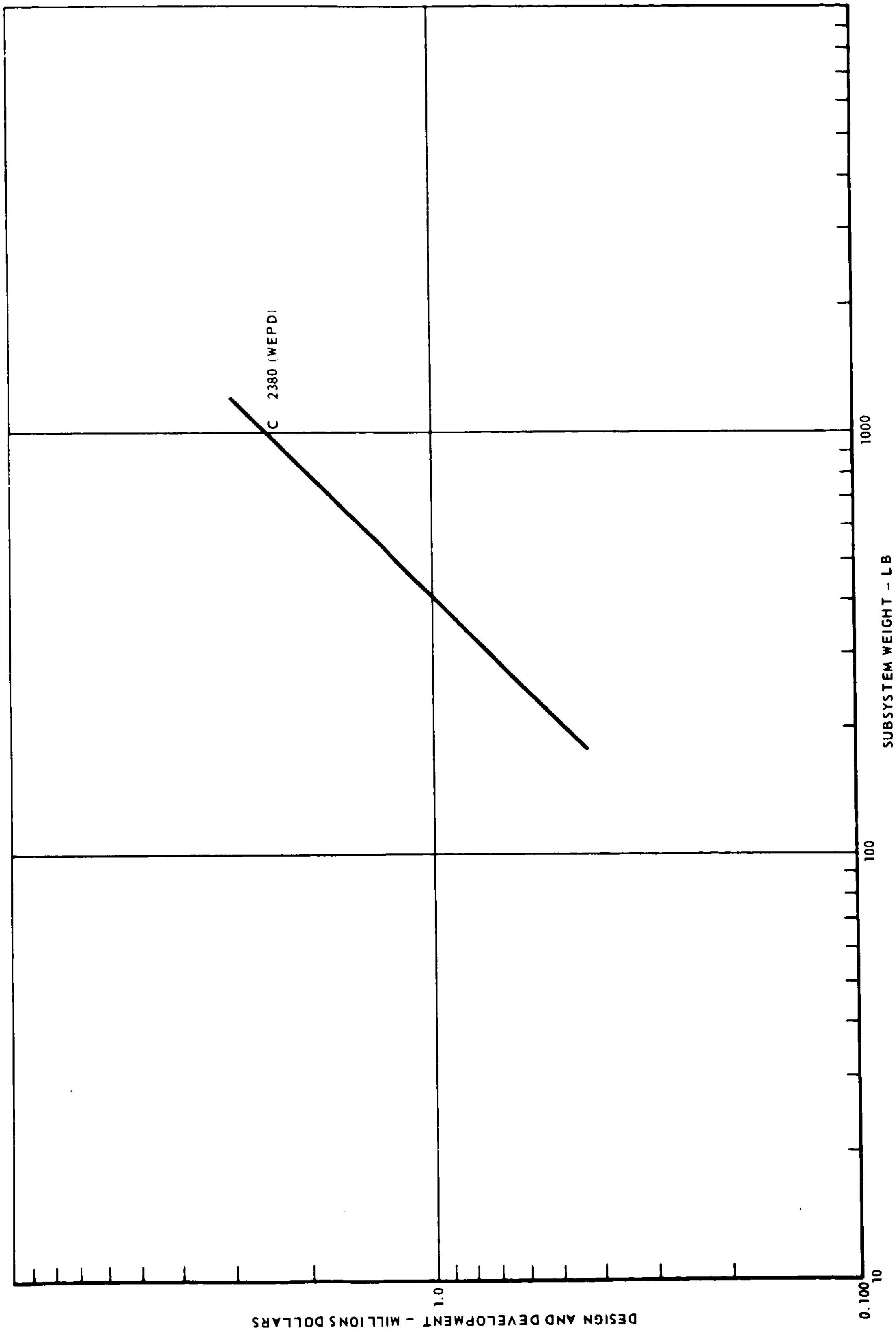


Figure 6–33

POWER SUPPLY AND ORDNANCE – FUEL CELLS
DESIGN AND DEVELOPMENT
MATERIAL, CFE, AND SUBCONTRACT

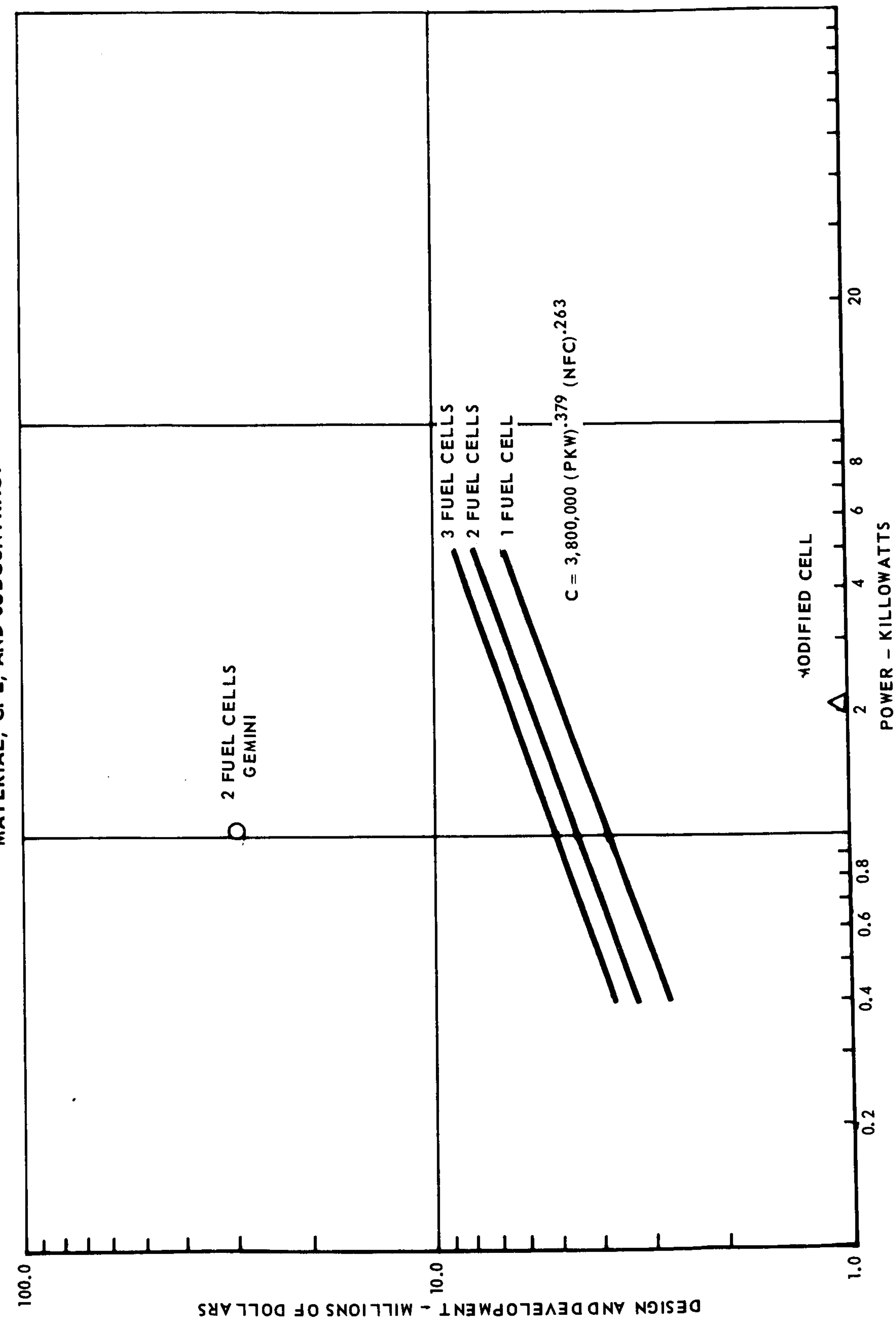
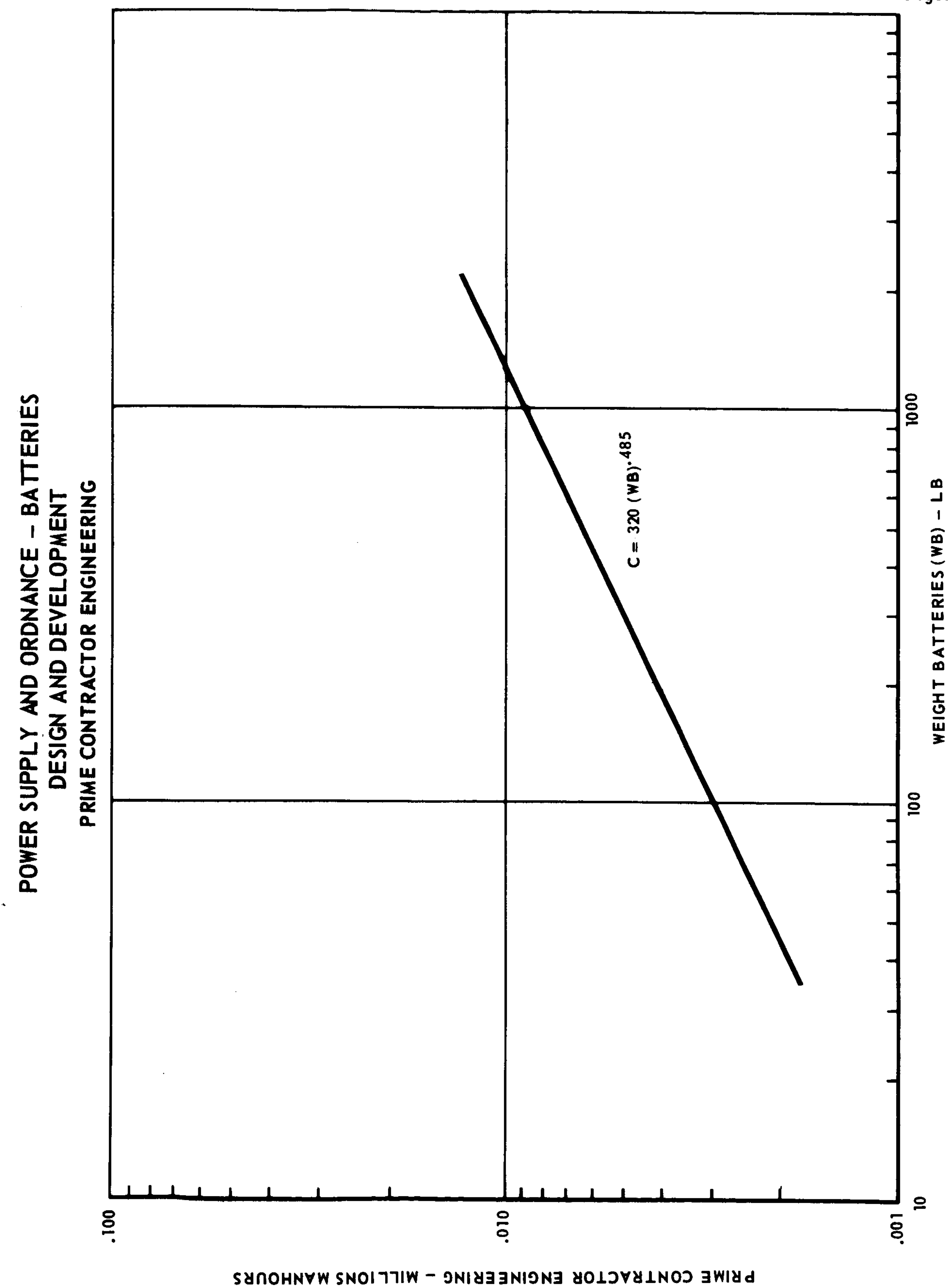


Figure 6-34


POWER SUPPLY AND ORDNANCE – BATTERIES
DESIGN AND DEVELOPMENT
PRIME CONTRACTOR ENGINEERING
C = 320 (WB)$^{.485}$
WEIGHT BATTERIES (WB) – LB
10
100
1000
.100
.010
.001
PRIME CONTRACTOR ENGINEERING – MILLIONS MANHOURS

subcontractor development cost CER utilizes the energy output of the battery as the estimating parameter.

6.2.5.4 Reactant Supply System - The prime contractor engineering CER for this subsystem is discussed in Paragraph 6.2.3. The subcontract cost CER is based on Gemini and vendor supplied data. The CER developed is below the Gemini cost history because the Gemini cost includes a major redesign. Two sets of tanks were developed, one for the short missions and one for the long missions. See Figure 6-35. The Gemini data was adjusted to exclude the redesign effort. The resulting cost and CER is comparable to cryogenic tank design cost as supplied by Bendix. The estimating parameter is total energy output of the system.

6.2.5.5. Hydraulics and Pneumatics - All of the hydraulics and pneumatics CER's are based on F-4 aircraft cost history. See Figures 6-36 and 6-37.

6.2.5.6 Ordnance - These CER's are based on the Gemini cost history. See Figures 6-38 and 6-39.

6.2.6 Environmental Control System (ECS) - The prime contractor engineering CER for this subsystem is discussed in Section 6.2.3. The subcontractor cost CER is given in Figure 6-40. The CER is based on Gemini, Mercury, and a Hamilton Standard quote for this study. The CER for the storable gas supply was estimated at 80% of the cryogenic gas supply.

6.2.7 Avionics - The prime contractor engineering CER's for the Avionic subsystems are discussed in Section 6.2.3. Since the Avionic subsystems as defined for this study are only sensitive to concept and vehicle configuration, estimates have been made for each concept rather than developing a CER for the subcontract cost. The estimates are based on Gemini cost history and vendor supplied data. The estimated costs are given in Table 6-4; the concept definitions are included in Volume II, Book 1.

Figure 6–35

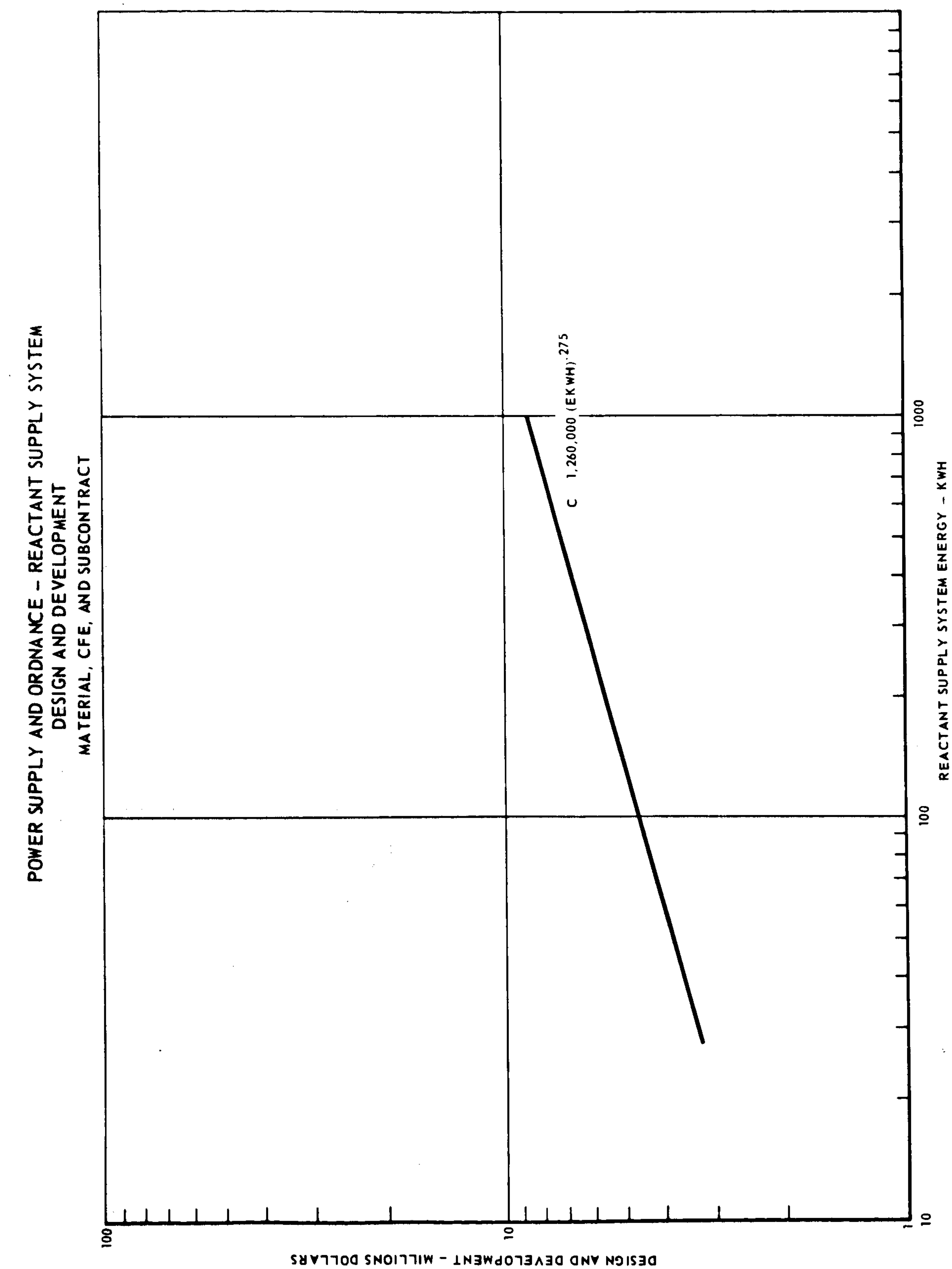

POWER SUPPLY AND ORDNANCE – REACTANT SUPPLY SYSTEM
DESIGN AND DEVELOPMENT
MATERIAL, CFE, AND SUBCONTRACT
C 1,260,000 (EKWH)^.275
REACTANT SUPPLY SYSTEM ENERGY – KWH
10
100
1000
DESIGN AND DEVELOPMENT – MILLIONS DOLLARS
100
10
1

Figure 6–36

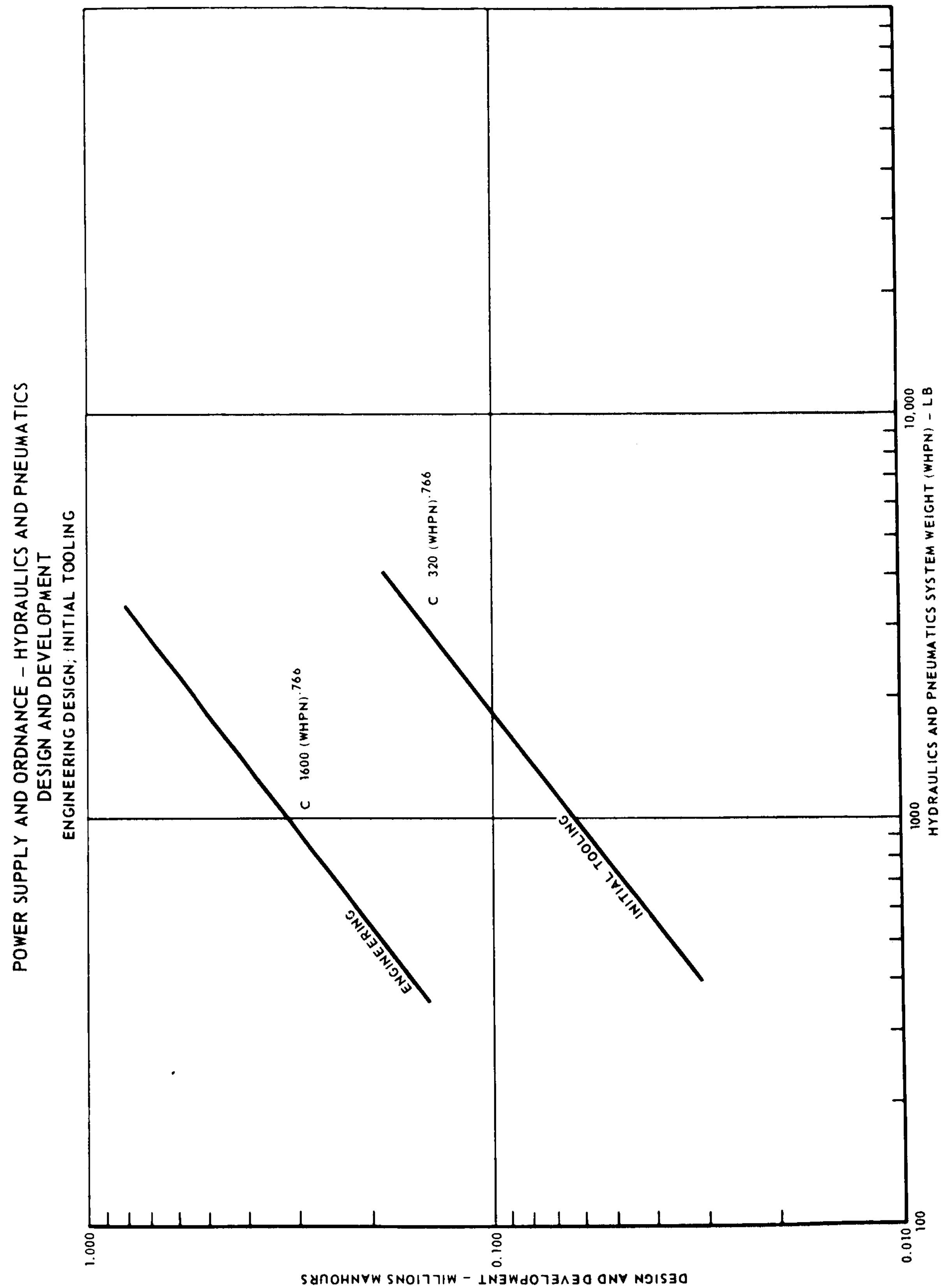

POWER SUPPLY AND ORDNANCE – HYDRAULICS AND PNEUMATICS
DESIGN AND DEVELOPMENT
ENGINEERING DESIGN; INITIAL TOOLING
C 1600 (WHPN)$^{.766}$
ENGINEERING
C 320 (WHPN)$^{.766}$
INITIAL TOOLING
100
1000
10,000
HYDRAULICS AND PNEUMATICS SYSTEM WEIGHT (WHPN) – LB
1.000
0.100
0.010
DESIGN AND DEVELOPMENT – MILLIONS MANHOURS

Figure 6–37

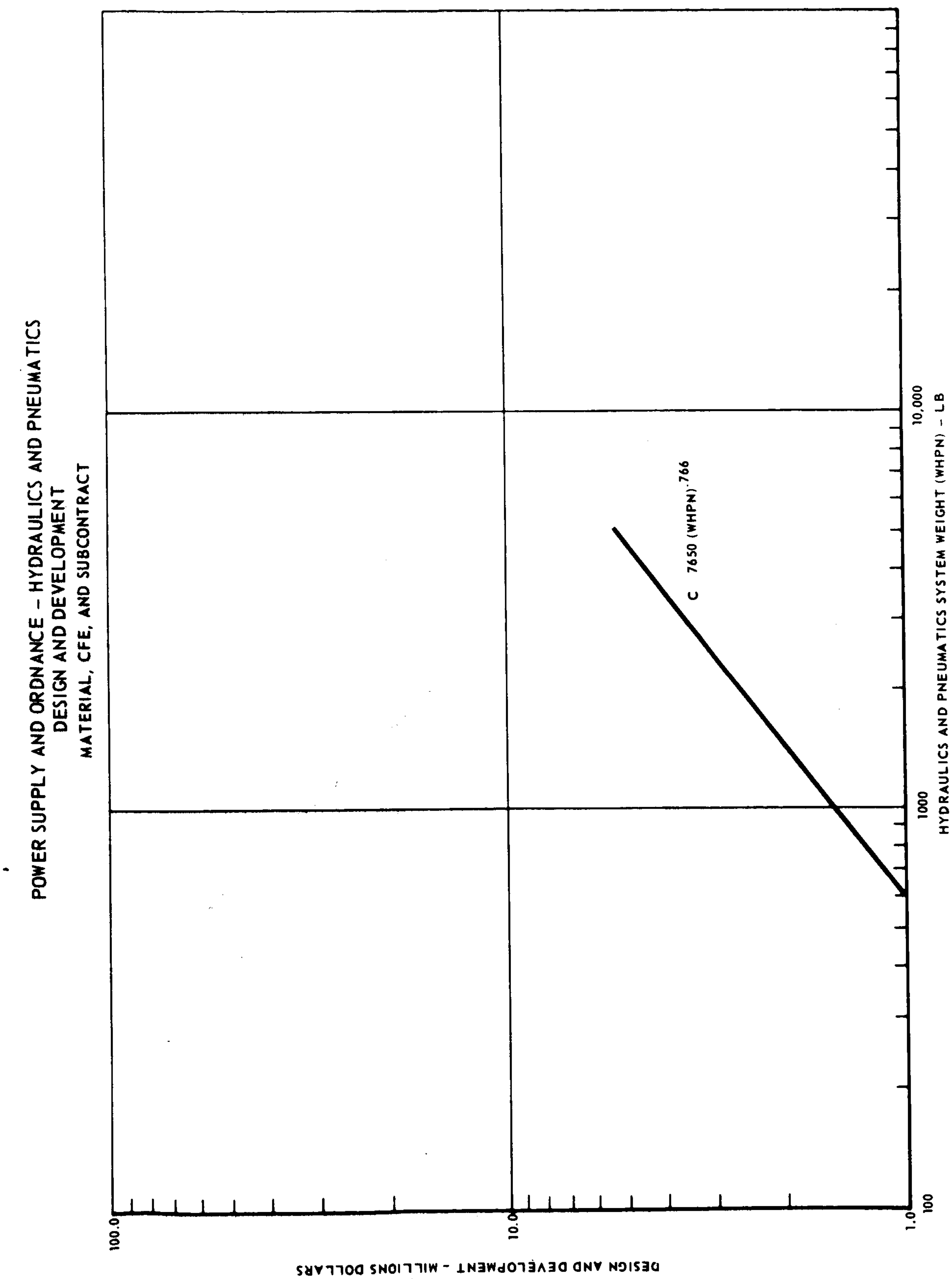

POWER SUPPLY AND ORDNANCE – HYDRAULICS AND PNEUMATICS
DESIGN AND DEVELOPMENT
MATERIAL, CFE, AND SUBCONTRACT
C 7650 (WHPN).766
100
1000
10,000
HYDRAULICS AND PNEUMATICS SYSTEM WEIGHT (WHPN) – LB
100.0
10.0
1.0
DESIGN AND DEVELOPMENT – MILLIONS DOLLARS

Figure 6–38

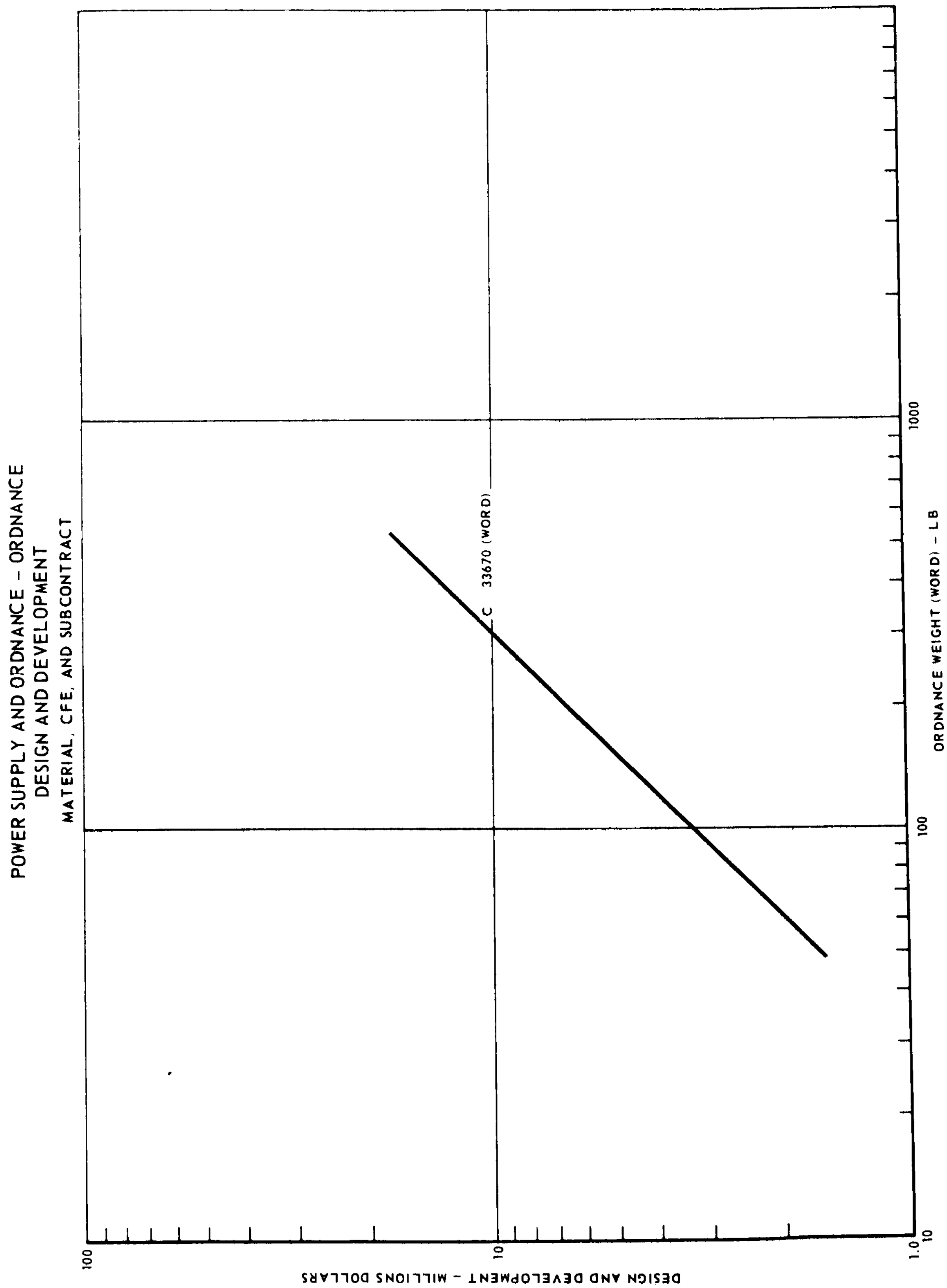

POWER SUPPLY AND ORDNANCE – ORDNANCE
DESIGN AND DEVELOPMENT
MATERIAL, CFE, AND SUBCONTRACT
C 33670 (WORD)
ORDNANCE WEIGHT (WORD) – LB
10
100
1000
DESIGN AND DEVELOPMENT – MILLIONS DOLLARS
1.0
10
100

Figure 6–39

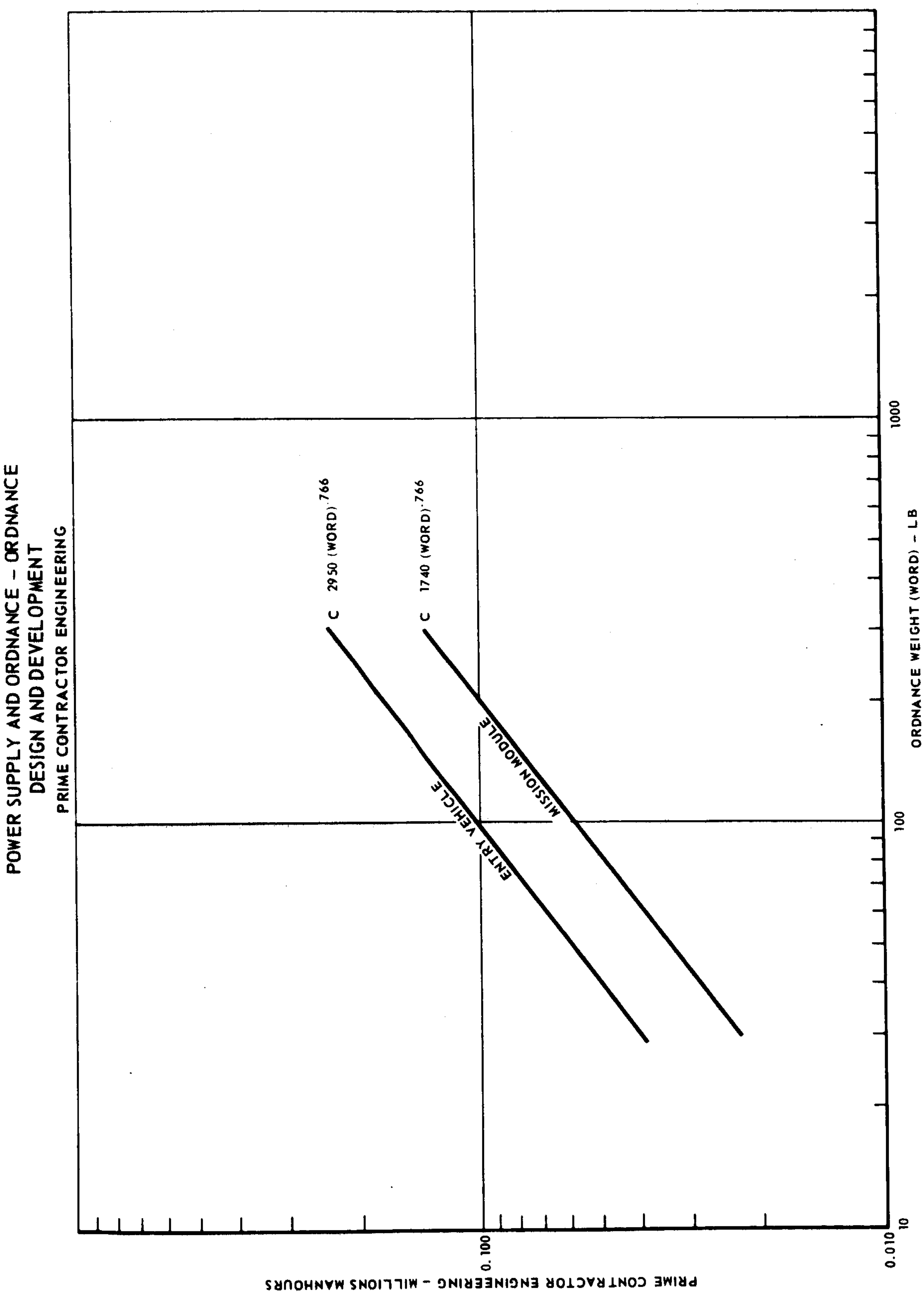

POWER SUPPLY AND ORDNANCE – ORDNANCE
DESIGN AND DEVELOPMENT
PRIME CONTRACTOR ENGINEERING
C 2950 (WORD)$^{.766}$
C 1740 (WORD)$^{.766}$
MISSION MODULE
ENTRY VEHICLE
ORDNANCE WEIGHT (WORD) – LB
10
100
1000
PRIME CONTRACTOR ENGINEERING – MILLIONS MANHOURS
0.010
0.100

Figure 6-40

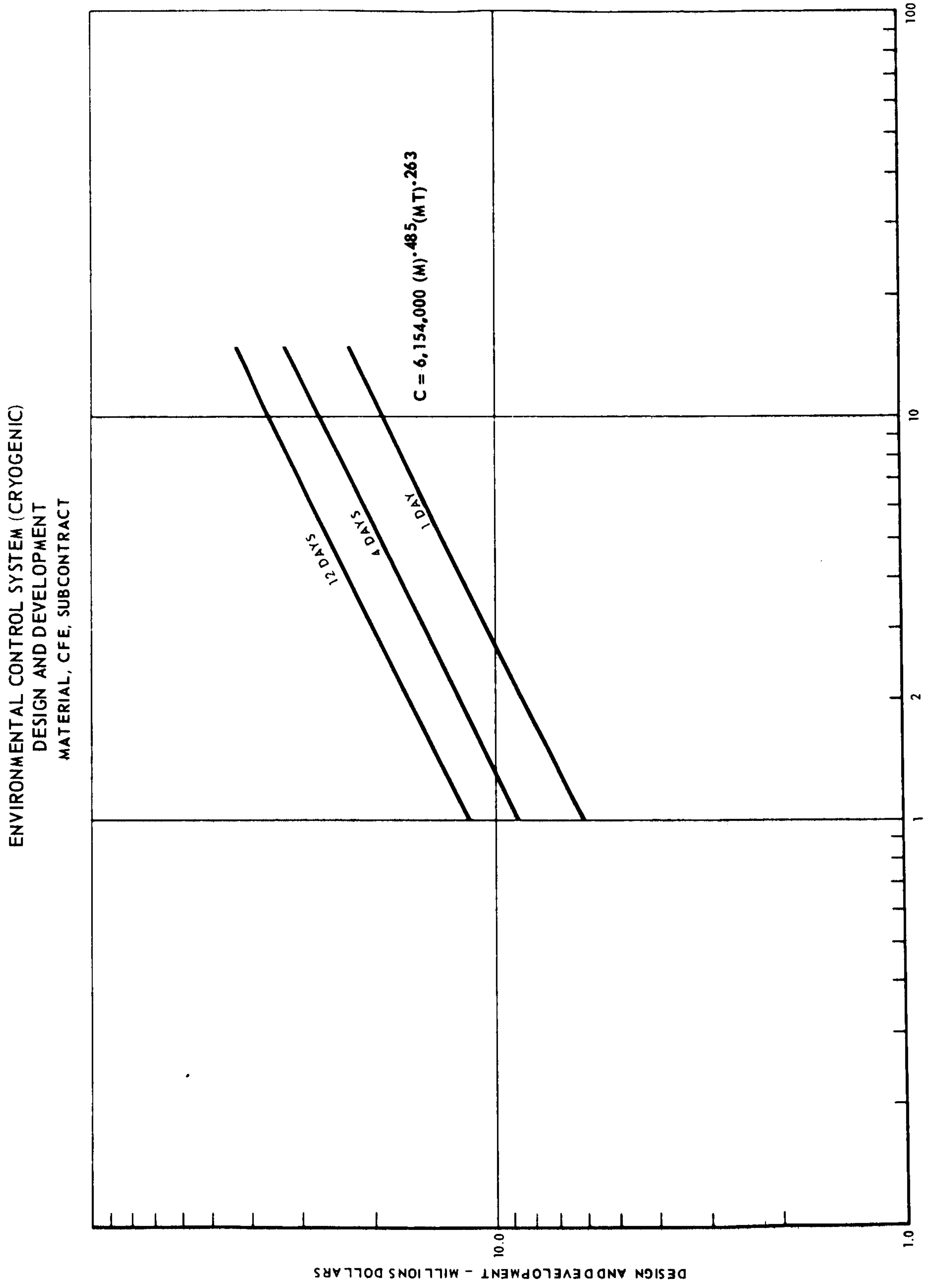

ENVIRONMENTAL CONTROL SYSTEM (CRYOGENIC)
DESIGN AND DEVELOPMENT
MATERIAL, CFE, SUBCONTRACT
C = 6,154,000 (M)$^{.485}$(MT)$^{.263}$
1 DAY
4 DAYS
12 DAYS
1
2
10
100
NUMBER OF MEN (M)
1.0
10.0
DESIGN AND DEVELOPMENT - MILLIONS DOLLARS

Table 6-4

Avionic Development Cost	
Guidance & Control Concept	Telecommunication
GC 1 or 5 = $66,000,000	TC 1 = $22,400,000
GC 2 or 6 = 71,000,000	TC 2 or 4 = 30,400,000
GC 3 or 7 = 73,000,000	TC 3 or 5 = 25,400,000
GC 4 or 8 = 73,000,000	

The crew station CER's are based on the Gemini cost history. See Figures 6-41 and 6-42.

6.2.8 Propulsion - The propulsion CER's have been developed by type of engine and the necessary additional components required to complete a particular propulsion subsystem. The CER's developed for each component are then used for each of the propulsion subsystems defined as applicable. Each subsystem, as applicable, is therefore sensitive to type of engines and the estimating parameters utilized.

The liquid engine subsystems are segregated into engines, tanks, and lines, valves and miscellaneous (LVM). The LVM category includes the residue of the propulsion subsystem after the engines and propellant tanks are extracted.

Four classifications of liquid rocket engines are considered, segregated as to cooling, feed system and propellant type. Only one solid rocket motor (SRM) CER was developed and is used for all the SRM applications in this study.

Figure 6-43 presents a summary of the four liquid engine design and development (D&D) CER's. The engines have been classified as follows:

1. Radiation cooled, pressure fed, storable propellant (lowest cost)
2. Ablative cooled, pressure fed, storable propellants
3. Regenerative cooled, pump fed, LOX/RP and storable propellants
4. Regenerative cooled, pump fed, cryogenic propellants (highest cost)

In general, pump fed engines are more expensive than pressure fed engines; regenerative cooling is more expensive than ablative or radiative cooling; ablative more expensive than radiative; and cryogenic propellants are more expensive than storable propellants. LOX/RP propellant engines are

Figure 6–41

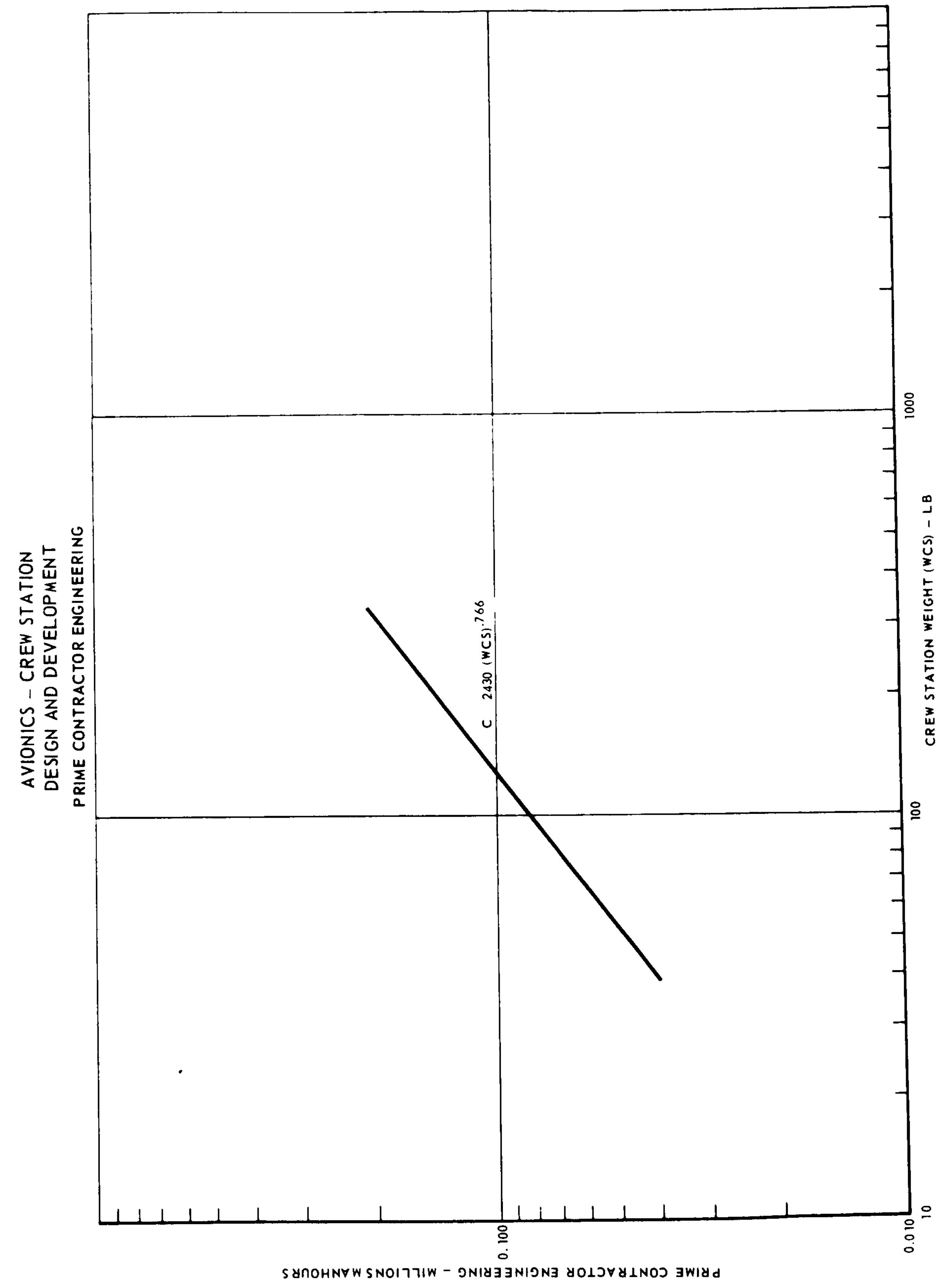

AVIONICS - CREW STATION
DESIGN AND DEVELOPMENT
PRIME CONTRACTOR ENGINEERING
C 2430 (WCS).766
1000
100
10
CREW STATION WEIGHT (WCS) - LB
0.100
0.010
PRIME CONTRACTOR ENGINEERING - MILLIONS MANHOURS

Figure 6-42

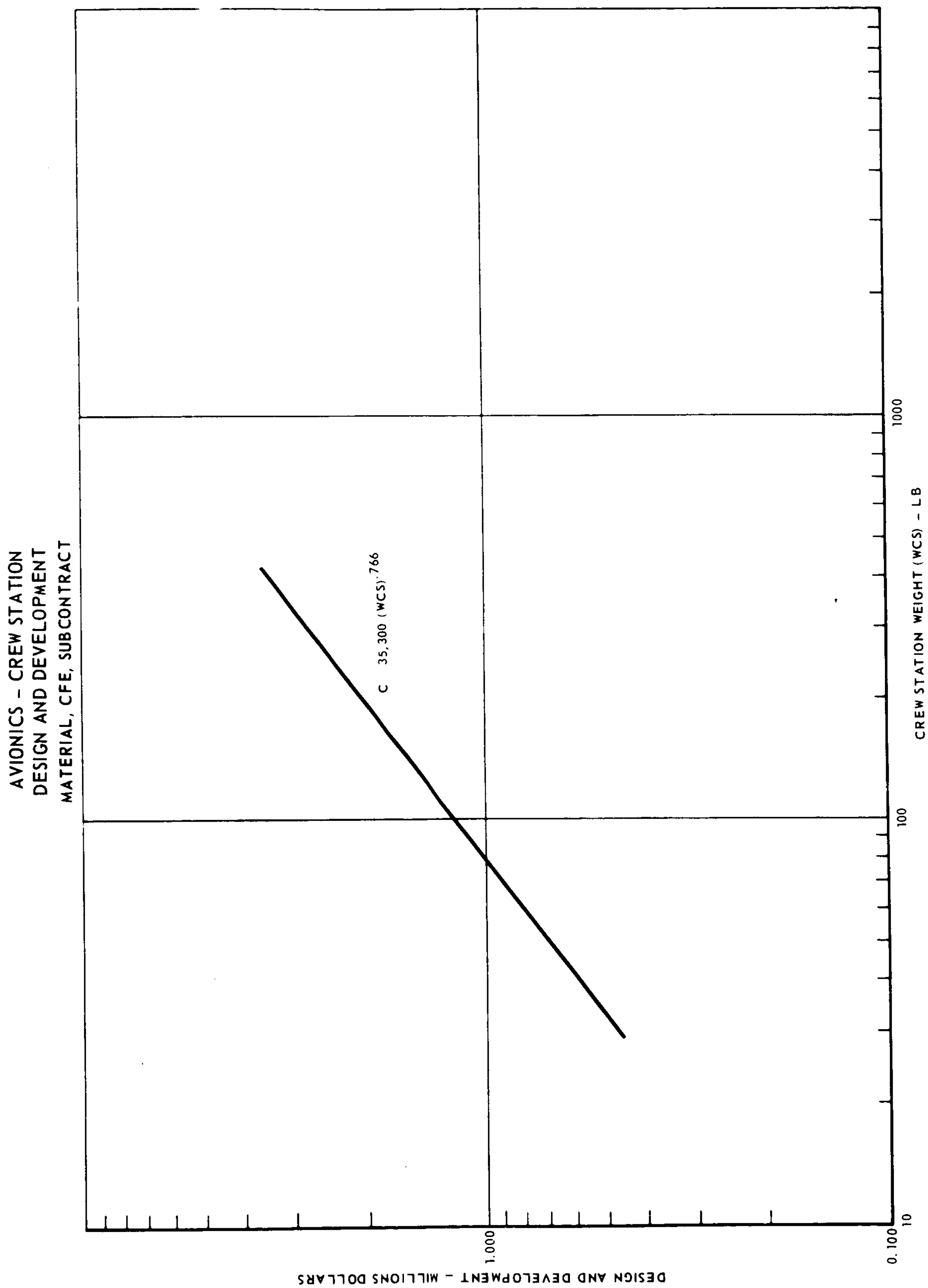
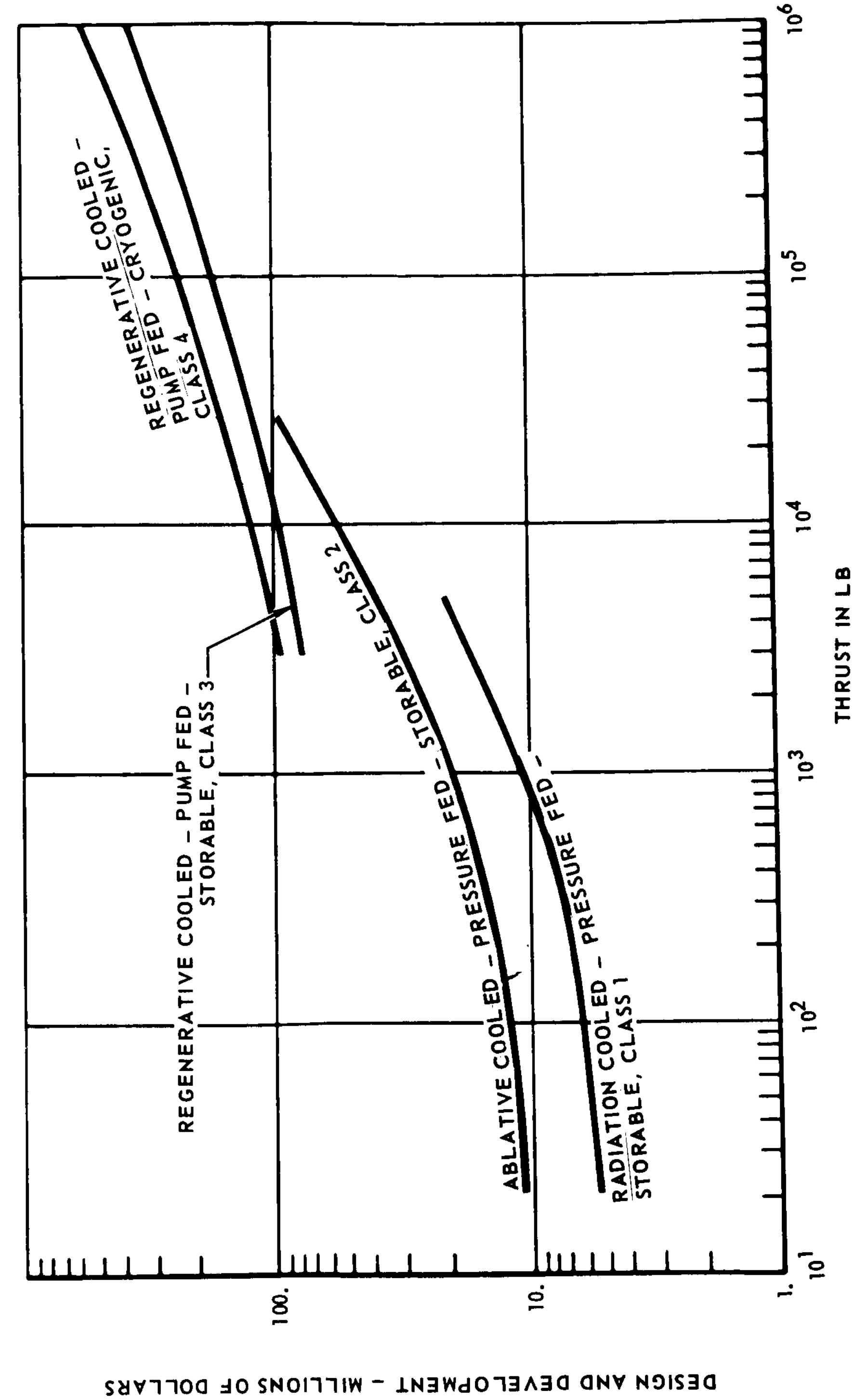

AVIONICS - CREW STATION
DESIGN AND DEVELOPMENT
MATERIAL, CFE, SUBCONTRACT
C 35,300 (WCS)·766
CREW STATION WEIGHT (WCS) - LB
1000
100
10
1.000
0.100
DESIGN AND DEVELOPMENT - MILLIONS DOLLARS

Figure 6-43

PROPULSION – LIQUID ENGINES
DESIGN AND DEVELOPMENT MATERIAL, CFE, AND SUBCONTRACT



similar in their cost history to storable propellant engines and were analyzed together as one family (Class 3 engines).

The range of thrusts required for the study are great and consequently extrapolations beyond the data base of each class of engines were made. The Class 1 and 2 engines are considered for the relatively low thrust range and Classes 3 and 4 for the relatively high thrust range. A problem arises in the intermediate thrust range where all four classes of engines come into play. Care must be exercised in this thrust regime.

During the analysis, many performance parameters are considered. A regression analysis was applied to the data, using thrust, engine weight, chamber pressure, and specific impulse as the independent parameters. These parameters were considered individually as well as in various combinations but the limited data in some cases resulted in equations which exhibited trends inconsistent with physical characteristics. Therefore, the technique employed involves close scrutinization of each data point and rationalizations as to why some data points are high or low relative to the majority of the data of a specific engine class. For example, some of the engines represent merely upgrading of an older engine's performance characteristics while other engines represent pushing the state-of-the-art or are new technology developments. These extreme cases were weighted in the CER derivations. The CER's developed are the results of a faired line through the data.

Class 1 - Radiation cooled, pressure fed, storable propellants

$(F = 25 - 5000)$

$$C = 5.0 \times 10^6 + 4.86 \times 10^4 \ (F)^{.678}$$

Class 2 - Ablative cooled, pressure fed, storable propellants

$(F = 25 - 50{,}000)$

$$C = 10.0 \times 10^6 + 8.40 \times 10^4 \ (F)^{.678}$$

Class 3 - Regenerative cooled, pump fed, LOX/TP and storable propellants

$(F = 2000 - 2 \times 10^6)$

$$C = 50.0 \times 10^6 + 8.65 \times 10^5 \ (F)^{.422}$$

Class 4 - Regenerative cooled, pump fed, LOX/H_2 propellants

$(F = 2000 - 1 \times 10^6)$

$$C = 50.0 \times 10^6 + 1.405 \times 10^6 \ (F)^{.422}$$

where C = Design and Development Cost
F = Vacuum Thrust, lbs.

The Class 1 engine CER is based on three data points and a close examination of the entire family of CER's. Sufficient data were not available to establish a CER for this class by itself. Therefore, cost values and trends of the entire family of engines was utilized for the derivation of this CER. It appear reasonable to assume that the Class 1 and 2 engine D&D costs will vary consistently. See Figure 6-44 for a plot of the CER.

The Class 2 engine CER has a fairly good data base over the range of thrust to be estimated. Nine data points were available and reasonable correlation was established. These data were the basis for establishing the shape of the curve that is used for the engine CER's. See Figure 6-45.

The Class 3 engine CER is shown in Figure 6-46. Seven data points were available for this engine class. Previous propulsion studies have indicated that the slope (thrust exponent) of LOX/RP, storable and cryogenic propellant engines are similar if the cooling and feed systems are of the same type. The available data further substantiates this. A very reasonable correlation of the data was established.

The Class 4 engines are presented in Figure 6-47. The data available includes the RL-10, J-2, and 3 data points provided by Pratt & Whitney. The shape of the curve used here was established by the Class 3 engine.

Pratt & Whitney has been developing a high chamber pressure (3000 psia) cryogenic propellant engine but it is still in the D&D phase. P & W has supplied three data points of this class of engines for this study. The P & W proposed engine D&D cost data appears to fall in line with the RL-10 and J-2 data points.

The study requires a cost estimating technique for variation in chamber pressure. The RL-10 and J-2 engines represent 300 and 632 psia chamber pressure respectively. The P & W data represents 3000 psia data but appears optimistic. It has been assumed that a 1.50 factor shall apply to high chamber pressure D & D costs over the CER values shown in Figure 6-47.

Figure 6-44

PROPULSION – LIQUID ENGINES
RADIATION COOLED – PRESSURE FED – STORABLE PROPELLANT (CLASS 1)
DESIGN AND DEVELOPMENT MATERIAL, CFE, AND SUBCONTRACT

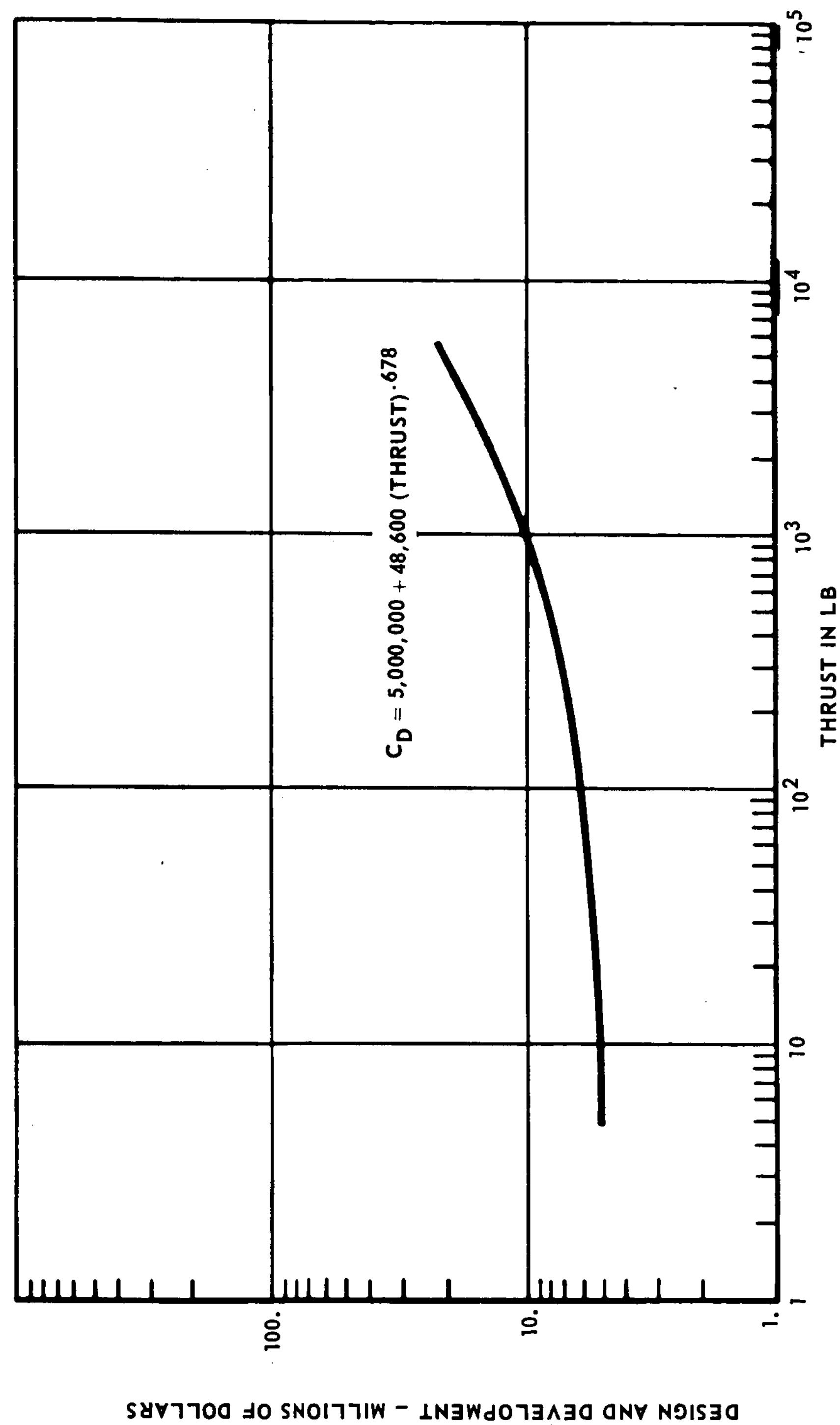
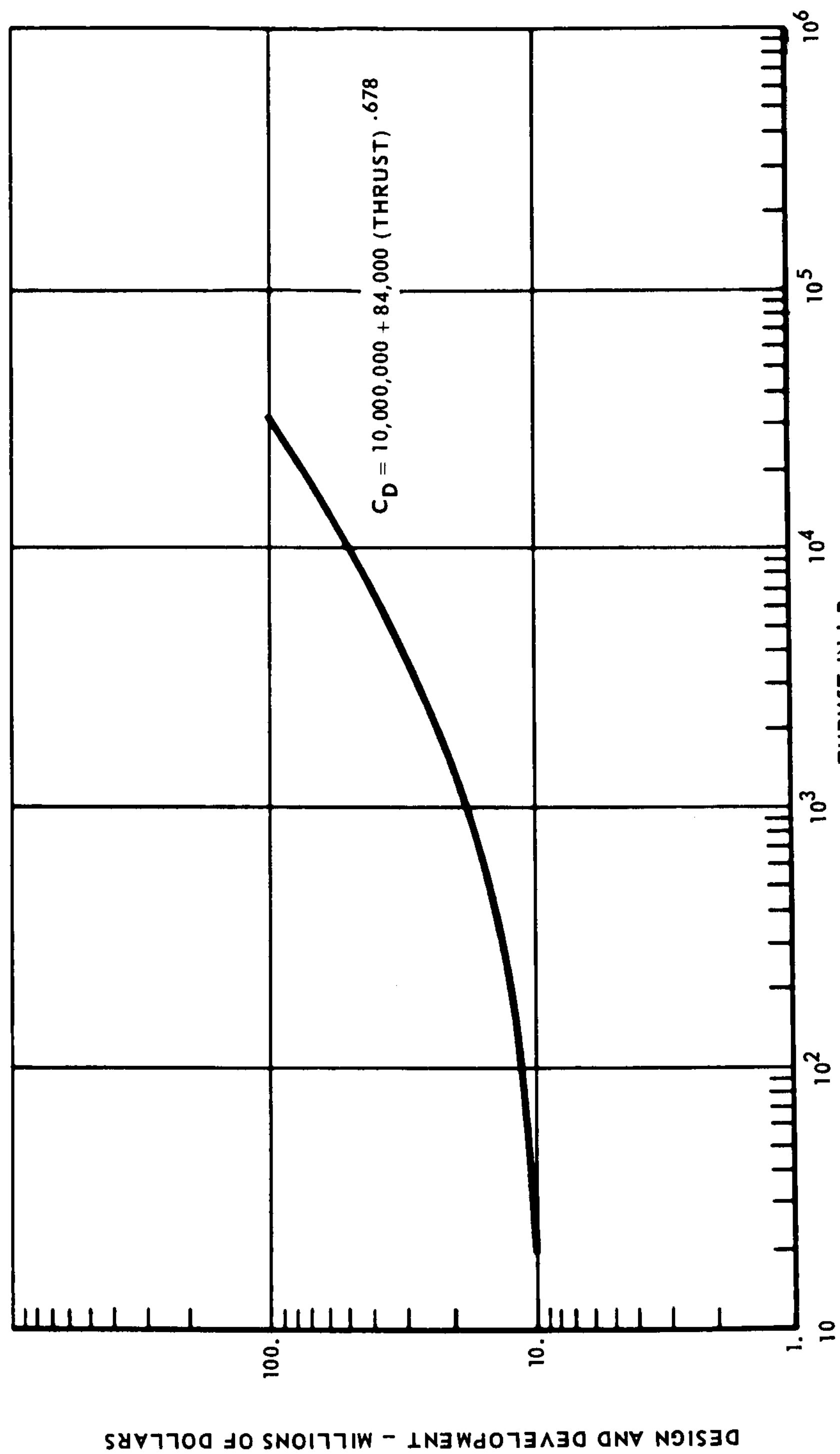


Figure 6–45



PROPULSION – LIQUID ENGINES
ABLATIVE COOLED – PRESSURE FED – STORABLE PROPELLANT (CLASS 2)
DESIGN AND DEVELOPMENT MATERIAL, CFE, AND SUBCONTRACT

Figure 6-46

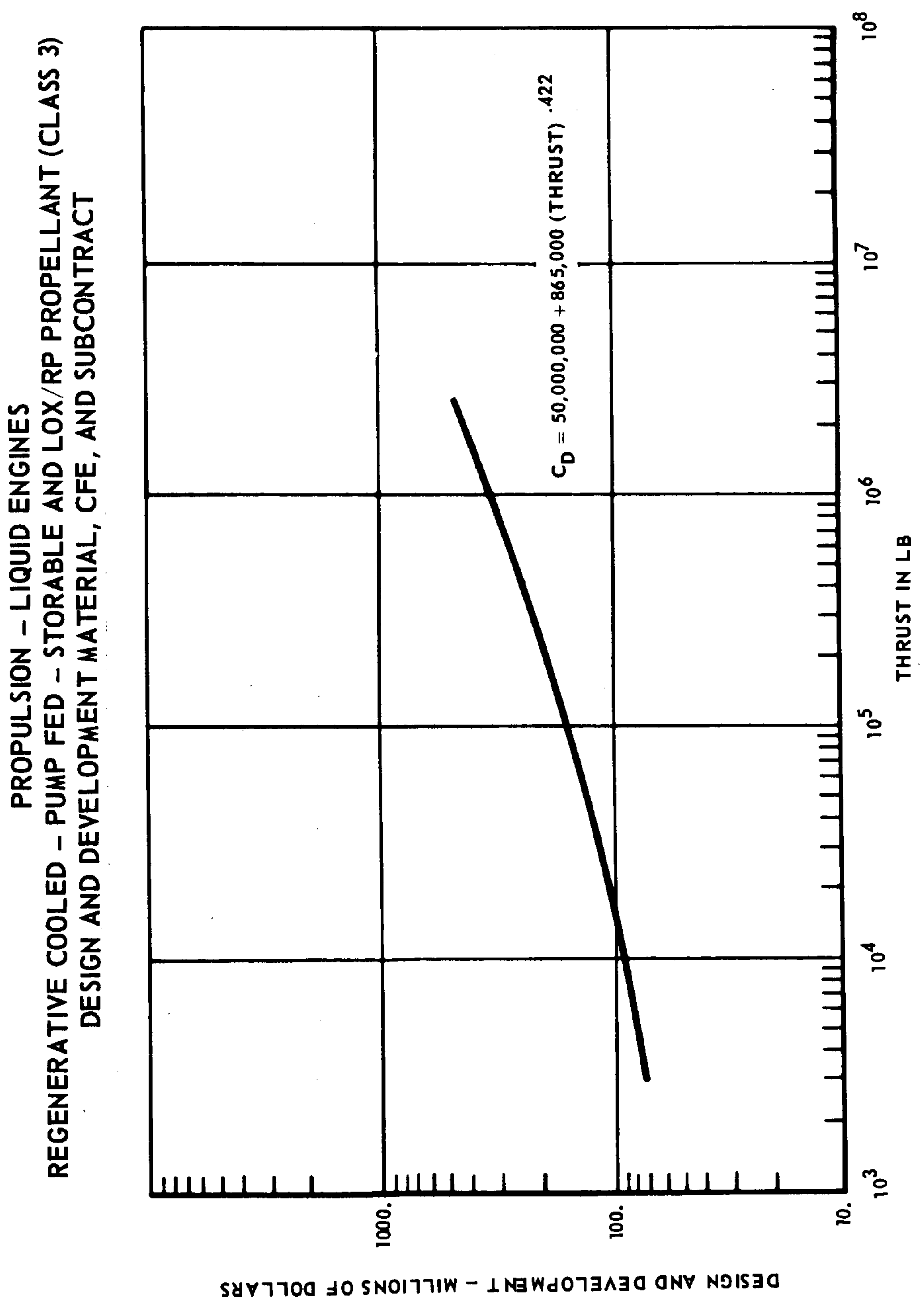
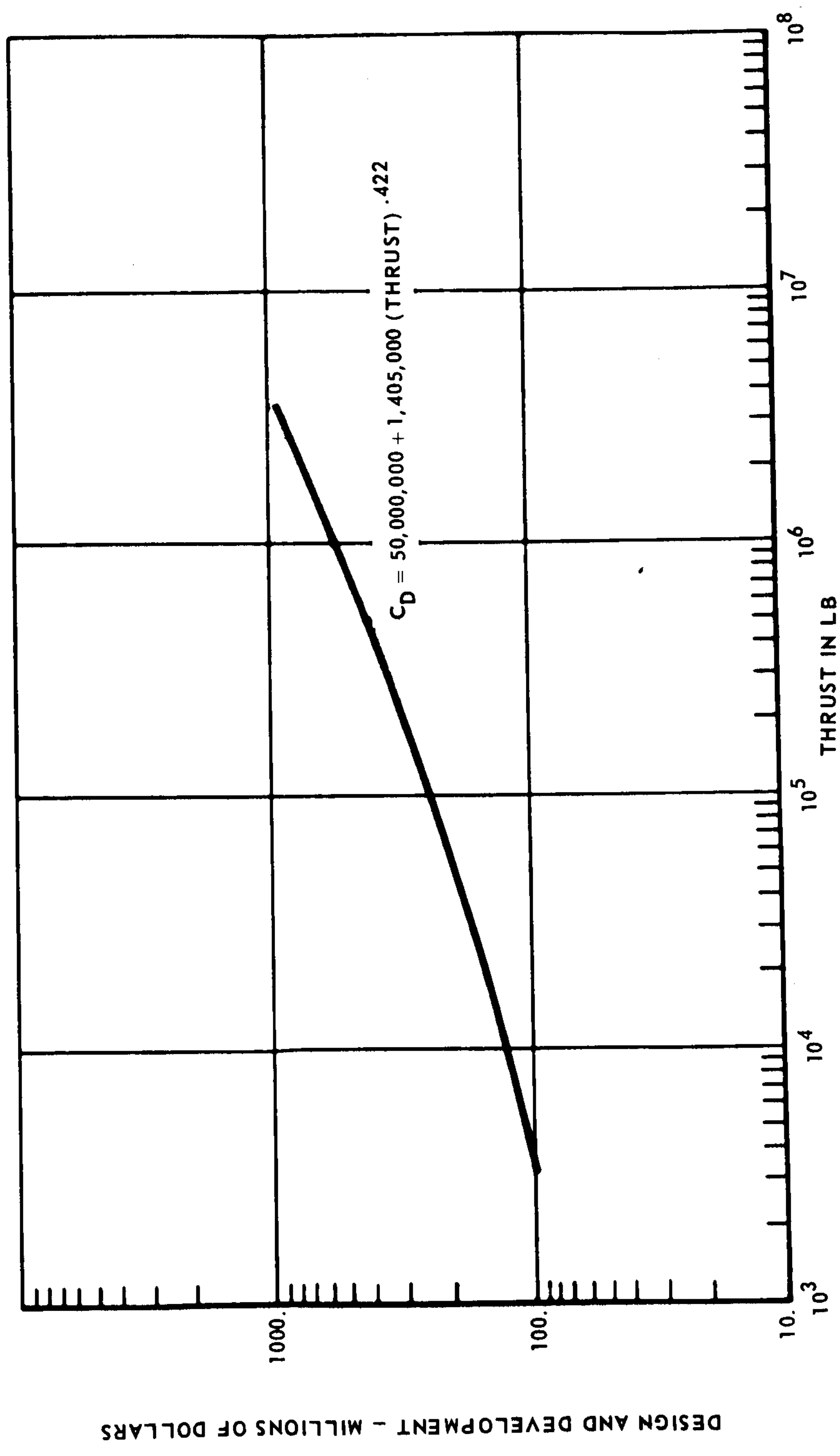

PROPULSION – LIQUID ENGINES
REGENERATIVE COOLED – PUMP FED – STORABLE AND LOX/RP PROPELLANT (CLASS 3)
DESIGN AND DEVELOPMENT MATERIAL, CFE, AND SUBCONTRACT
$C_D = 50,000,000 + 865,000\ (\text{THRUST})^{.422}$
THRUST IN LB
10^3
10^4
10^5
10^6
10^7
10^8
DESIGN AND DEVELOPMENT – MILLIONS OF DOLLARS
10.
100.
1000.

Figure 6–47

PROPULSION – LIQUID ENGINES
REGENERATIVE COOLED – PUMP FED – CRYOGENIC PROPELLANT (CLASS 4)
DESIGN AND DEVELOPMENT MATERIAL, CFE, AND SUBCONTRACT



The D&D liquid engine CER's were developed excluding the cost of propellants used during the D&D program. The propellant costs are estimated by the following CER:

$$C = (KPRL)\ (F)$$

where

C = Total Cost of Propellants

KPRL = Cost of a given propellant in dollars per pound of engine vacuum thrust.

F = Vacuum thrust per engine in lbs.

The KPRL factor was derived based on the following equation.

$$KPRL = \frac{[HFBT]}{ISP}\left[(KUO)\ (CO)\left(\frac{MR}{MR+1}\right) + (KUF)(CF)\left(1 - \frac{MR}{MR+1}\right)\right]$$

where

HFBT = Total hot fire burn time, seconds

KUO = Oxidizer utilization factor for boil-off and losses.

KUF = Fuel utilization factor for boil-off and losses.

CO = Oxidizer cost, \$/Lb.

CF = Fuel cost, \$/Lb.

MR = Oxidizer to fuel mixture ratio

ISP = Vacuum specific impulse, seconds

In this analysis, HFBT equals 300,000 seconds. The development program through PFRT accounts for 65,000 seconds, and the qualification time, including "engine-to-vehicle" integration testing, is 235,000 seconds. Tables 6-5 and 6-6 present a summary of the values for the equation. Table 6-6 is derived from the data in Table 6-5 and the above equation.

The CER for the solid rocket motor (SRM) is based on 5 data points, 2 of which are proposed motors. The same parameter used for first unit cost has been used here since the scatter of the data was so great. The SRM costs are insignificant relative to the other propulsion subsystems and do not warrant further research for CER development at this time. See Figure 6-48 for a plot of the CER.

Figure 6-48

PROPULSION - SMALL SOLID ROCKET MOTORS
DESIGN AND DEVELOPMENT
MATERIAL, CFE, SUBCONTRACT

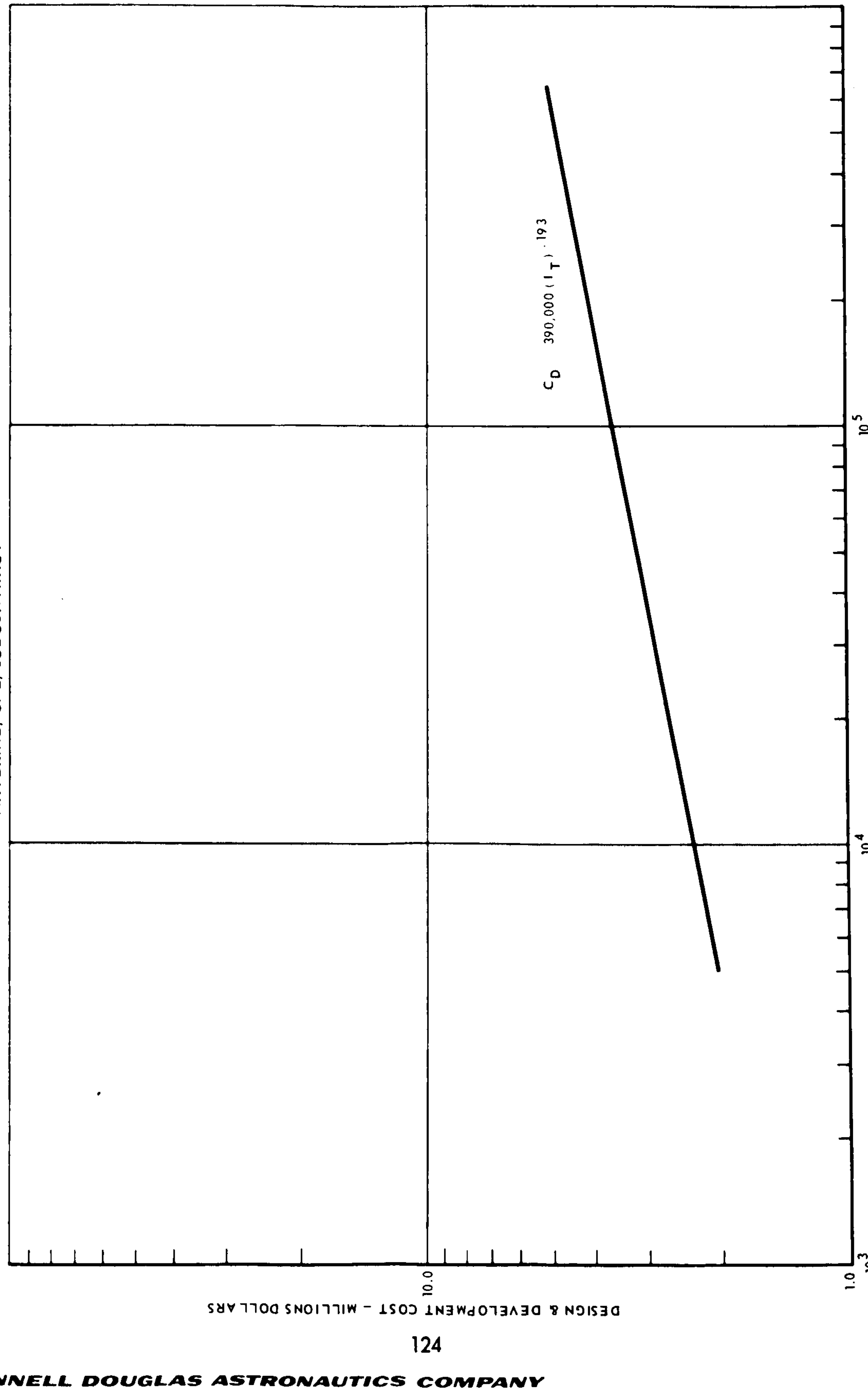


Table 6-5

Propellant Cost and Utilization Characteristics		
Propellant Type	Utilization Factor-KU	Propellant Cost Dollars/Lb.
O_2	1.54	.02
H_2	2.50	.35
F_2	1.01	1.00
FLOX	1.01	.90
CH_4	1.10	.03
NTO	1.10	.065
A-50	1.10	.50

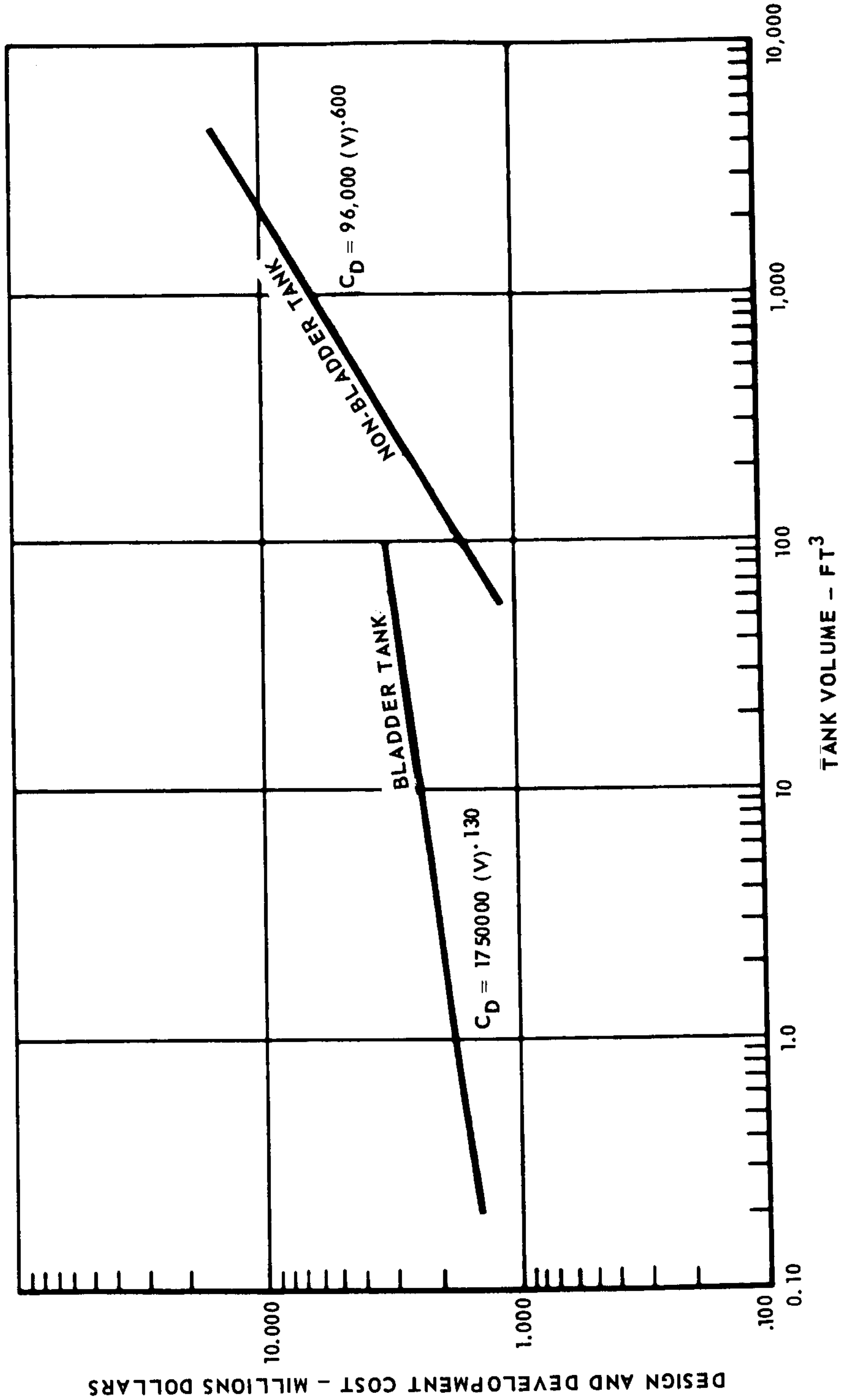
Table 6-6

Design and Development Propellant Cost Factor			
Propellant Combination	ISP Seconds	Mixture Ratio	KPRL
O_2/H_2	450	6	101.
F_2/H_2	460	12	652.
$FLOX/CH_4$	390	4	564.
NTO/A-50	320	2	209.

The propellant tank CER's are presented in Figure 6-49. Tanks that are an integral part of the structure, i.e., load carrying members and the large tanks for the launch upper stage propulsion subsystem, are considered part of the structure subsystem. The propulsion subsystem tanks are relatively small tanks separately attached to the main structure. A few large tank data (Thor and S-IVB main) points were included so that the data range could be extended in order to evaluate the effects of such design considerations. The costs are derived as a function of tank volume (V) expressed in cubic feet. No difference in cost between spherical or cylindrical shape tanks was evidenced from the data. A distinction between a tank having and not having a bladder

Figure 6–49

PROPULSION – TANKS
DESIGN AND DEVELOPMENT
MATERIAL, CFE, SUBCONTRACT



is made. All tanks for the propulsion subsystems, except the launch upper stage, are considered as subcontracted effort. The following CER's were derived.

Bladder Tank, $C = 1.75 \times 10^{6} (V)^{.130}$

Non-Bladder Tank, $C = 9.6 \times 10^{4} (V)^{.600}$

where

C = Design and Development Cost, dollars

V = Tank Volume, $Ft.^{3}$

The lines, valves, and miscellaneous (LVM) category is defined as the propulsion subsystem residue after the engine and tank assemblies are removed. It includes all hardware items that the prime contractor must supply (either fabricate or subcontract) in addition to the engines and propellant tanks in order to constitute a complete functional propulsion subsystem. Similar to the propellant tanks, the LVM category is considered as subcontract effort for the smaller propulsion subsystems and only the launch upper stage subsystem is a prime contractor effort. The data is restricted to two MDAC vehicles, Gemini and the S-IVB stage of the Saturn V launch vehicle. The Gemini data are representative of a subcontracted cost while the S-IVB is indicative of a prime contractor in-house effort. The following CER's were developed for the LVM category.

Subcontract Effort	$C = 1.265 \times 10^{6} (W)^{.410}$
Prime Contractor Engineering (Launch Upper Stage)	$C = 2.32 \times 10^{5} (W)^{.570}$

where:

C = Design and Development Cost, dollars

W = Total propulsion system weight, lbs.

See Figure 6-50 for the subcontract cost CER and Figure 6-51 for the prime contractor cost CER.

6.2.9 Aerospace Ground Equipment (AGE) - AGE includes the design, development, and fabrication of the ground support equipment. It includes equipment for handling, transportation, component test, subsystem test, servicing, maintenance and operational equipment, launch and checkout, and refurbishment equipment.

Figure 6–50

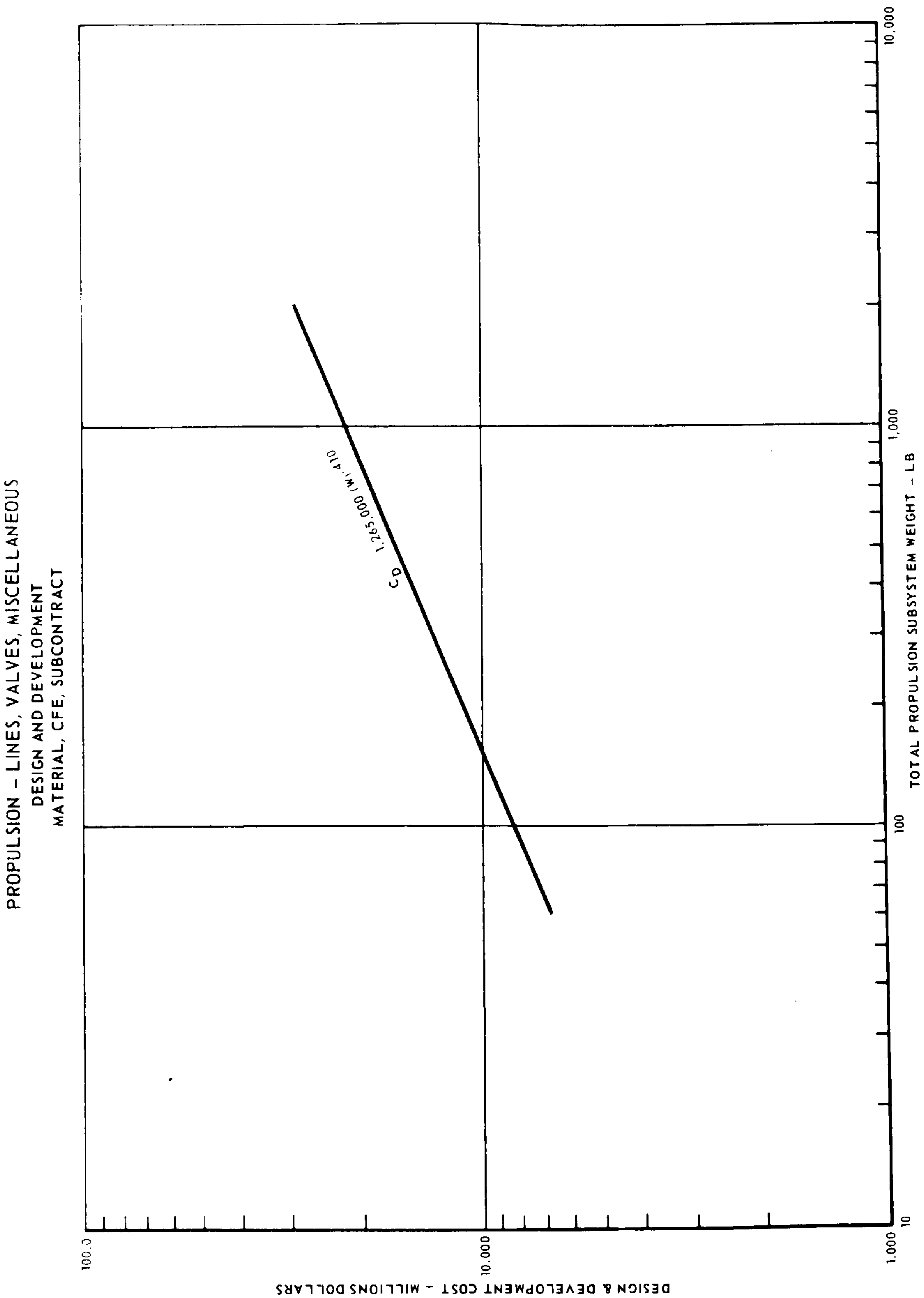
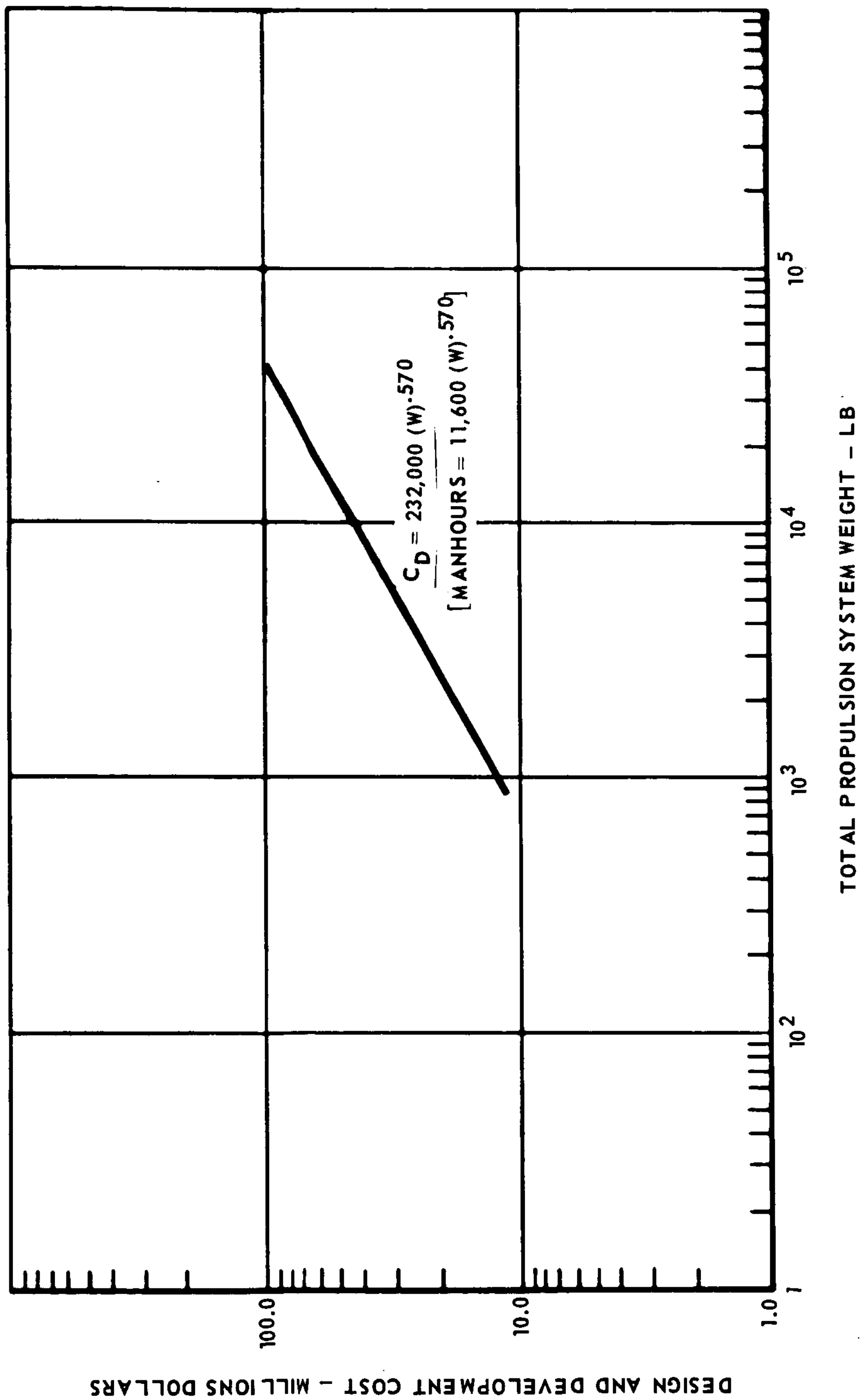

PROPULSION – LINES, VALVES, MISCELLANEOUS
DESIGN AND DEVELOPMENT
MATERIAL, CFE, SUBCONTRACT
C_D 1,265,000 (W)$^{.410}$
TOTAL PROPULSION SUBSYSTEM WEIGHT – LB
10,000
1,000
100
10
DESIGN & DEVELOPMENT COST – MILLIONS DOLLARS
100.0
10.000
1.000

Figure 6-51

PROPULSION – LAUNCH UPPER STAGE SYSTEM
DESIGN AND DEVELOPMENT
PRIME CONTRACTOR ENGINEERING



The Gemini cost history was used for developing the CER's. The cost history was divided into non-recurring (design and development) and recurring (fabrication). Existing detail cost history was used to further segregate the cost history into structural type equipment (handling, alignment and measurements, and a portion of the facility support equipment) and non-structural subsystems support equipment. Each of the cost categories (which includes prime contractor engineering, prime contractor production, and material, CFE and subcontract) has been related to the basic design and development cost or first unit cost.

6.2.10 RDT&E Phase Facilities - This study has assumed that existing facilities will be fully utilized. However, there are certain expected costs involved in modifying these facilities and activating the launch facilities, and in providing the recovery site facilities.

6.2.10.1 Recovery Site Facilities - For this cost model it was assumed that the recovery sites would be procured during the RDT&E phase, and that the same quantity would be required for both the RDT&E and the operational phases. The cost of these is sensitive to recovery philosophy and landing mode. Approximately 5% of the cost is prime contractor labor in a consulting capacity during the construction of the sites or modification of the ships.

Labor Costs - The prime contractor labor costs are a small portion of the total, and the estimate is provided by the following equation.

$$\begin{aligned} CPRFRS = \{&(LLM)[(1-E2S)(16.468) + (E2S)(NS)(2.065) + (VLM)(1-E2s) \\ &(-1.330) + (E2S)(NS)(.205)] + (1-LLM)(11.540)\}\{(3125)(KLRS)\} \end{aligned}$$

where

CPRFRS = Recovery Site Facilities Labor Cost, dollars
E2S = Existing site network switch 0 = No, 1 = Yes
NS = Number of existing sites (2 or more)
VLM = Vertical landing mode switch 0 = No, 1 = Yes
LLM = Land landing mode switch 0 = No, 1 = Yes
KLRS = Composite labor rate

Material Costs - The material costs or subcontract costs for construction of the recovery sites forms the bulk of the costs. These are estimated by the equation:

$$RFACM = \frac{304\ (CPRFRS)(KMCS)}{KLRS}$$

where:

RFACM = Recovery Site Facilities Material Costs, dollars
KMCS = Economic esclation factor

6.2.10.2 Launch Site Facility Activation - This cost category provides for the costs the prime contractor incurs in getting the launch site facilities ready for the test flight program. This involves getting the equipment installed and checked out prior to delivery of the first vehicle.

Labor Costs - The labor costs are the major portion of these costs, and are estimated by the equation:

$$CPRFLA = KLRS\ (220{,}102)$$

where:

CPRFLA = Launch Site Facility Activation Labor Costs, dollars
KLRS = Composite labor rate

Material Costs - The material and subcontract costs are estimated to be 25% of the labor costs. For a baseline labor rate of $16.00 this is equivalent to $4.00 and the CER is:

$$RFACM2 = \frac{4.0\ (KMCS)(CPRFLA)}{KLRS}$$

where:

RFACM2 = Launch Site Facility Activation Material Costs, dollars
KMCS = Economic esclation factor

6.2.10.3 Launch Site Facilities Modification - This cost category is sensitive to size and complexity of the vehicle which is measured by the first unit costs. It is a subcontracted cost, or even a cost to the customer rather than one administered by the prime contractor. The CER is:

$$RFACM3 = 3376\ (TSC)^{.485}\ (KMCS)$$

where:

RFACM3 = Launch Site Facilities Modification Material Costs, dollars
TSC = First Unit vehicle cost
KMCS = Economic esclation factor

6.2.11 Trainers and Simulators - Trainers and simulators are based on Gemini cost history and are calculated as a function of first unit cost. Aircraft cost history has shown this method to be a good indication of the cost of trainers.

6.2.12 System Engineering - System engineering includes all the subsystems common effort. Since this is a common effort in support of all the subsystems, the CER for system engineering has been derived as a function of the prime contractor's cost for design and development of the subsystems. The CER is based on Gemini and S-IVB cost history.

6.2.13 RDT&E Phase Air Drop Test Operations - The development of any vehicle utilizing gliding parachutes or horizontal land landing will require an air drop test program to investigate the aerodynamic handling of the vehicle. A separate analysis established the values used in this CER which include operation and modification of the carrier or mother aircraft, the pro-rated share of the Edwards FRC, the personnel costs and the air drop hardware spares, AGE, and maintenance. This CER reflects both the test program and a follow on training program; the test program lasts ten to eleven months followed by a 20 month training program. At least 45 drops will be made during this time.

Labor Costs - The cost of the engineers and mechanics necessary to support the Air Drop operations is estimated by the equation:

$$\begin{aligned} RSTOAP &= RSTOAP = (2100)(KLRS)(60 + 65)+(3652)(KLRS)(35+40)+13{,}340{,}000(KMCS) \\ &= 536{,}400\ (KLRS) + 13{,}340{,}000\ (KMCS) \end{aligned}$$

where:

RSTOAP = Air Drop Test Operations Labor Cost, dollars

KLRS = Composite labor rate (remote site)

KMCS = Economic escalation facto

Material Costs - The material costs account for spares, repair and maintenance materials, the cost of operating the carrier airplane, and the prorated costs of the test center. The CER to estimate this cost is:

where:

$$RSTOAM = [.623\ (CAHTS)]\ (KMCS)$$

RSTOAM = Air Drop Test Operations Material Costs

CAHTS = Air Drop vehicle thermo/structure group cost for 3 vehicles

KMCS = Economic esclation factor

6.2.14 Ground Test Operations - The ground test operations include S/C wind tunnel testing, S/C thermal qualification testing, and remote site static fire testing of the launch upper stage propulsion system.

6.2.14.1 Wind Tunnel - Wind tunnel testing cost has been developed as a constant cost for each of the two basic configurations defined for this study. The cost data has been derived from the F-4 aircraft, an advanced fighter aircraft detail estimate, and the Gemini spacecraft. The parameters selected for estimating the cost include the number of wind tunnel occupancy hours required by tape of test (i.e. aerodynamic force and moment, thermodynamic, structural dynamic, etc.) and the required manhours per occupancy hour. The number of manhours per tunnel occupancy hour for the fighter aircraft are considerably more than the ballistic spacecraft. Based on these data it is evident that the model design and fabrication, and the actual testing cost is a function of vehicle configuration. To derive the manhours per occupancy hour for the M2-F2, the available cost data (manhours per occupancy) were plotted versus the configuration factor as developed for the basic engineering design cost (See Figure 6-52). Using the data from this plot, the average manhours per occupancy hour for the M2-F2 was estimated by type of wind tunnel test. The ballistic spacecraft is based on the Gemini cost history. The number of occupancy hours by type of test is based on a detail estimate.

6.2.14.2 Thermal Qualification Test - Thermal qualification testing of the spacecraft is based on Gemini and Mercury cost history. Total dry weight of the complete spacecraft is used as the estimating parameter. See Figure 6-53.

6.2.14.3 Launch Upper Stage Propulsion Static Fire Testing - The static test operations include the activities involved in remote site operations as well as the prime contractor's in-plant support. The ground test program includes all effort at the test center to plan, conduct, and analyze tests on the Battleship stage, Facilities Checkout stage, and acceptance test firing on flight test stages. The following CER is based on the S-IVB test operations at the Sacramento test site and two test stands.

$$= [2.676 \times 10^5 + 4.95 \times 10^4 \text{ (QF1-1)}] \text{ (NE)}^{.260} \text{ (F)}^{.140} \text{ (KLRS)}$$

Figure 6-52

AVERAGE MANHOURS PER WIND TUNNEL OCCUPANCY HOUR VS CONFIGURATION FACTOR

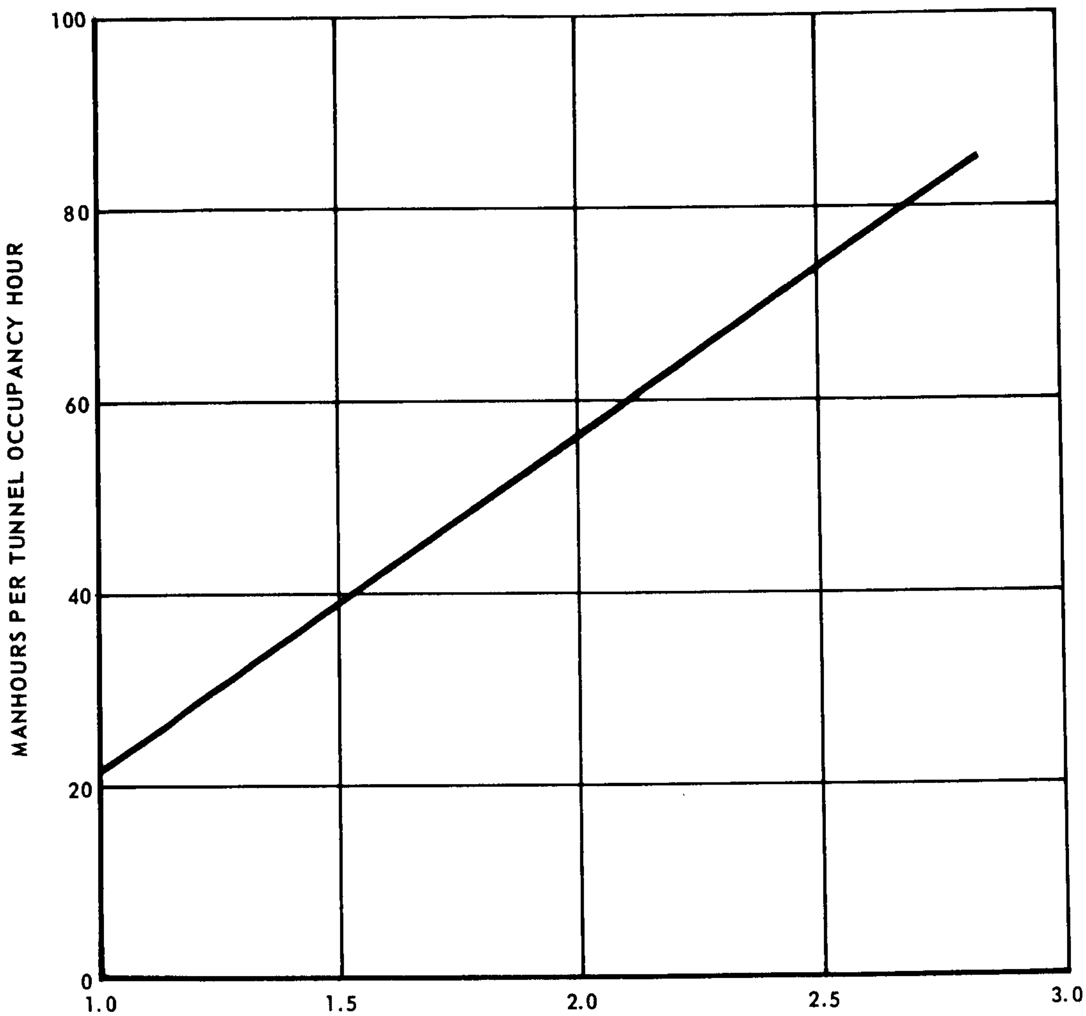
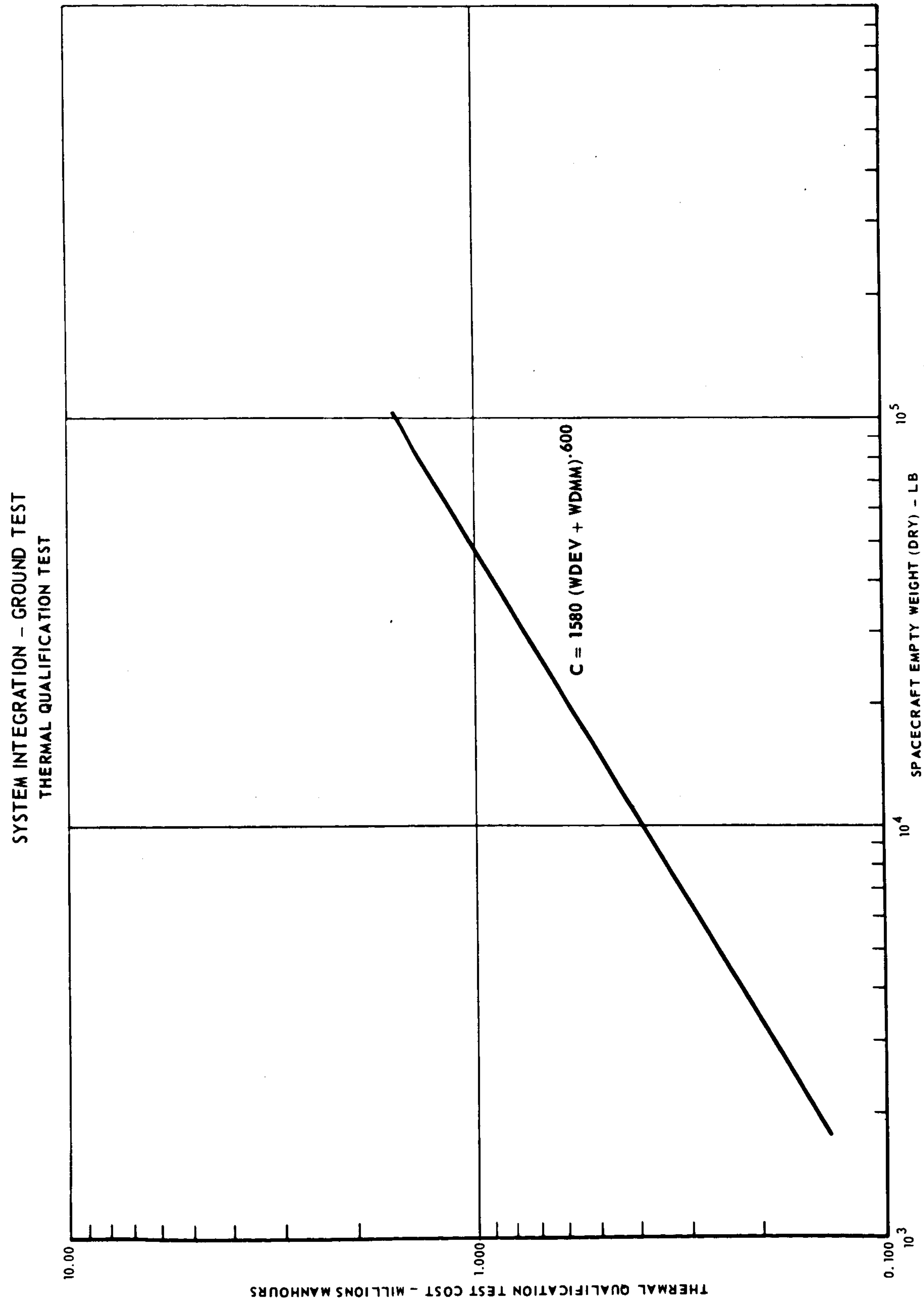


FIGURE 6–53


SYSTEM INTEGRATION – GROUND TEST
THERMAL QUALIFICATION TEST
C = 1580 (WDEV + WDMM)^.600
SPACECRAFT EMPTY WEIGHT (DRY) – LB
10^3
10^4
10^5
THERMAL QUALIFICATION TEST COST – MILLIONS MANHOURS
10.00
1.000
0.100

where

C	=	Development and Acceptance Test Operations Cost, dollars
QFI	=	Number of Acceptance Test Firing for flight test stages
NE	=	Number of engines per vehicle
F	=	Thrust per engine, lbs.
KLRS	=	Remote Site composite labor rate

Miscellaneous materials are required at the test site and are related to the manhour expenditures. This is $0.75 per manhour. The propellant costs are based on the CER that is presented in Section 6.2.8 with 20,000 seconds of full thrust burn time for development testing.

6.2.15 RDT&E Phase Boosted Flight Test Operations - The development program includes boosted flight operations for the flight test phase. Connected with this are the launch operations, launch area support, mission control support, AGE maintenance, facilities maintenance, transportation, recovery operations, and the air drop program operations. The CER's were developed from the data presented in Volume II, Book 2, with appropriate economic, operational philosophy, AGE philosophy, and size factors added. Various switches were provided to accommodate user input options and vehicle configuration options.

6.2.15.1 Launch Operations CER - The boosted flight launch operations costs are sensitive to vehicle size, launch operations philosophy, and economic factors. The costs include both labor or personnel costs and materials (propellants) costs for the spacecraft portion of the launch costs. In all of these CER's, the costs associated with the booster or launch vehicle are included in the launch vehicle cost model.

Labor Costs - The launch operations labor costs for the boosted flight operations of the development phase is estimated by the equation:

$$STOFP1 = KLRS \left\{ \sum_{N=1}^{QF2} (18{,}590\, N^{-.4} + 10{,}094\, N^{-.349} + 19{,}373\, N + 12{,}160\, N^{-.197} + 13{,}831\, N^{-.238} + 45{,}325\, N^{-1.006}) \left[2.11 \times 10^{-4} (TSC)^{.485}\right] + \frac{52.13 \times 10^{5}}{14 - 4\,(BAL)} (USP) \right\}$$

where: STOFP1 = Boosted Flight Launch Operations Labor Costs

USP = Integral upper stage propulsion switch 0 = No, 1 = Yes

QF2 = Number of development launches

BAL = Ballistic Configuration switch 0 = No, 1 = Yes

N = Number of launch attempts

TSC = First Unit Cost (structure and subsystems for E/V & M/M)

KLRS = Composite labor rate

Material Costs - The materials cost are the costs of propellants and gases for the boosted flight operations. The CER is:

$$STOFM1 = [(WLOH)(.1182) + (WLFH)(1.2825) + (WFOC)(.8395) + (WSTO)(.2310)] (QF2)(KMCS)$$

where:

STOFM1 = Boosted Flight Launch Operations Material Costs

WLOH = Bulk weight of O_2/H_2 in pounds per launch

WLFH = Bulk weight of F_2/H_2 in pounds per launch

WFOC = Bulk weight of FLOX/CH_4 in pounds per launch

KMCS = Economic esclation factor

The above equation includes boil-off and line loss allowances.

6.2.15.2 Launch Area Support CER - Supporting the RDT&E phase boosted flight launch operations is a sustaining force of personnel. The sustaining support force costs are dependent upon program duration and the number of launches, as well as economic factors, vehicle configuration and operational philosophy. For the CER it was assumed that the launch site force came into being nine months after the contract go-ahead. The length of the development program varied from 45 months to 73 months for a five-flight program, depending upon which configuration was being considered.

Labor Costs - The labor costs for the boosted flight launch area support costs are composed of the costs of a constant staffing and the costs of supporting each launch. The constant staff provides the liaison engineering, future planning and repair of government equipment. The equation for estimating these costs is:

$$STOFP2 = (KLRS)\left(\sum_{N=1}^{QF2} 76{,}301\, N^{-.314}\right)\left[2.11 \times 10^{-4}\,(TSC)^{.485}\right]$$

$$+ [30{,}281][36\,(MBV) + 55\,(IBV) + 44\,(MLB) + 64\,(ILB)]$$

where:

STOFP2 = Boosted flight launch area support labor costs

MBV = Configuration IA, IB, IC switch 0 = no, 1 = yes

KLRS = Composite labor rate

IBV = Configuration ID, IE, IF switch 0 = no, 1 = yes

MLB = Configuration IIA, IIB, IIC switch 0 = no, 1 = yes

ILB = Configuration IID, IIE, IIF switch 0 = no, 1 = yes

QF2 = Number of development launches

N = Number of attempted launches

TSC = First unit cost (structure + subsystem for E/V & M/M)

Material Costs - The material costs are estimated to be 10% of the base labor costs. The CER is:

$$STOFM2 = \frac{1.6\,(KMCS)(STOFP2)}{KLRS}$$

where:

STOFM2 = Boosted Flight Launch Area Support Material Costs

KMCS = Economic escalation factor

6.2.15.3 Mission Control Support CER - Mission control support costs are totally labor costs for prime contractor support to mission control and mission planning. It is essentially a constant staffing level operation. Therefore, the CER assumes a constant monthly manpower loading, and is sensitive only to program duration. As with the launch area support, this activity will begin nine months after contract go-ahead and will continue for 36 months to 64 months, depending upon the configuration, for a five-flight test program. The CER is:

$$STOFP3 = (KLRS)\ 6942\ [36\,(MBV) + 55\,(IVB) + 44\,(MLB) + 64\,(ILB)]$$

where:

STOFP3 = Boosted Flight Mission Control Support Labor Costs, dollars

MBV = Configuration IA, IB, IC switch 0 = no, 1 = yes

KLRS	=	Composite Labor rates	
IVB	=	Configuration ID, IE, IF switch	0 = no, 1 = yes
MLB	=	Configuration IIA, IIB, IIC switch	0 = no, 1 = yes
ILB	=	Configuration IID, IIE, IIF switch	0 = no, 1 = yes

6.2.15.4 Spacecraft AGE Maintenance CER - AGE maintenance connected with the boosted flight test launch operations is sensitive to operational philosophy and economic factors.

Labor Costs - The labor costs are estimated by this equation:

$$STOFP4 = (KLRS) \left(\sum_{N=1}^{QF2} 162{,}251\ N^{-.933} \right)$$

where:

STOFP4	=	Boosted Flight AGE Maintenance Labor Costs, dollars
QF2	=	Number of development launches
KLRS	=	Composite labor rate
N	=	Number of attempted launches

Material Costs - The boosted flight operations AGE maintenance materials costs are estimated to be 10% of the initial AGE cost or:

$$STOFM4 = .10\ (CRAGR)$$

where:

STOFM4	=	Boosted Flight AGE Maintenance Material Costs
CRAGR	=	Recurring initial AGE costs

6.2.15.5 Spacecraft Launch Facilities Maintenance CER - The facilities maintenance associated with the boosted flight test launch operations is influenced by the vehicle size, the operational philosophy and economic factors.

Labor Costs - Facilities maintenance is primarily a labor function. The labor costs are estimated by the equation:

$$STOFP5 = (KLRS) \left[\sum_{N=1}^{QF2} 38{,}218\ N^{-.831} \right] \left[2.11 \times 10^{-4}\ (TSC)^{.485} \right]$$

where:

STOFP5	=	Boosted Flight Facility Maintenance Labor Costs, dollars
QF2	=	Number of development launches

N	=	Number of launch attempts
TSC	=	Total first unit cost (structure and subsystem for E/V and M/M)

Material Costs - The material costs are assumed to be 1% of the initial facilities costs or:

SPOFM5 = .01 (CRFAC)

where:

SPOFM5	=	Boosted Flight Facility Maintenance Material Costs
CRFAC	=	Initial facilities cost

6.2.15.6 Recovery Operations CER - This CER differs from the previous CER's in that it is based upon total cost to the customer, rather than on cost to the prime, since realistically the prime contractor has little control or authority over recovery. The recovery force could number several hundred people, but only a few would be prime contractor personnel. Thus, this CER reflects the total cost to the customer. The CER is:

STOF6 = [{(1-VLM) [(1-E2S) (168,000) + (E2S) (NS) (84,000)] +
[VLM] [LLM] [(1-E2S) (240,000) + (E2S) (NS) (120,000)]+
200,000 + (VLM) (42,000) + (1-LLM) (528,000)} {QF2} +
{ [1-VLM] [1-E2S) (46,166) + (E2S) (NS) (21,500] +
[VLM] [LLM] [(1-E2S) (42,500) + (E2S) (NS) (19,333)] +
[1-LLM] [115,500] [36(MBV) + 55 (IVB) + 44 (MLB) + 64 (ILB)]}]
[KECON]

where:

STOF6	=	Boosted Flight Recovery Operations Costs, dollars	
VLM	=	Vertical Landing mode switch	0 = no, 1 = yes
E2S		Existing site network switch	0 = no, 1 = yes
NS	=	Number of existing sites (2 or more)	
LLM	=	Land landing mode switch	0 = no, 1 = yes
QF2	=	Number of development launches	
MBV	=	Configuration IA, IB, IC switch	0 = no, 1 = yes
IBV	=	Configuration ID, IE, IF switch	0 = no, 1 = yes
MLB	=	Configuration IIA, IIB, IIC switch	0 = no, 1 = yes
ILB	=	Configuration IID, IIE, IIF switch	0 = no, 1 = yes
KECON	=	Economic factor	

6.2.15.7 Launch Site Peculiar AGE - As a program evolves, AGE requirements at the launch site develop which were not recognized at the start of the program. These could be the result of new or changed regulations or procedures, or of newly identified requirements. This CER attempts to recognize this, and to provide estimates of the costs involved.

Labor Costs - The manpower costs involved are estimated by this equation:

$$CRPLSA = (KLRS)(814052)$$

where:

CRPLSA = Boosted Flight Launch Site Peculiar AGE Labor Cost, dollars

KLRS = Composite Labor rate

Material Costs - The material costs are estimated to be 15% of the labor costs, and the equation is:

$$STOFM7 = \frac{(2.4)(KMCS)(CRPLSA)}{KLRS}$$

where:

STOFM7 = Boosted Flight Launch Site Peculiar AGE Material Costs

KMCS = Economic esclation factor

6.2.15.8 Transportation CER - The cost of transporting the RDT&E test flight vehicles to the launch site is a function of the transportation mode and economic factors. These costs are assumed to be a sub-contracted cost or material cost. The CER for the cost model is:

$$STOFM8 = [QF2]\,[20{,}000\,(ATS) = 14{,}000\,(LTS) + 115{,}000\,(BTS)]\,[KMCS]$$

where:

STOFM8 = Boosted Flight Transporation Costs, dollars

QF2 = Number of development launches

ATS = Air Transport switch 0 = no, 1 = yes

LTS = Land transport switch 0 = no, 1 = yes

BTS = Barge transport switch 0 = no, 1 = yes

KMCS = Economic escalation factor

6.2.16 System Test Hardware - System test hardware includes all hardware procured or fabricated by the prime contractor in support of the airdrop test program, the ground test program, all development testing, and the boosted flight test program. All of the hardware is calculated as a function of first unit cost and quantity by subsystem.

6.2.16.1 Airdrop Test Hardware - The subsystems that are included in the airdrop vehicle are the minimum required to perform the airdrop test program. Each subsystem is estimated as a percentage of the first unit cost or is a fixed value dependent on the subsystem requirements. Airdrop hardware is required for all lifting body configurations and all ballistic configurations that utilize a sailwing for recovery. When the entry vehicle dry weight exceeds 16,000 pounds a scale model is designed and fabricated because of carrier aircraft limitations. The cost of the scale model is fixed and is based on a test case calculation at the scale model size. The scale model engineering design cost was estimated at 925,000 manhours and is included with the sustaining engineering when the scale model is required. The scale model initial tooling cost was estimated at 225,000 manhours and is included with the sustaining tooling when the scale model is required. See Appendix C for a complete list of the CER's for the airdrop hardware. The structural equations included the type of material and construction complexity factor so that the structure is adjusted to an all aluminum airframe.

6.2.16.2 Ground Test Hardware - Ground test hardware includes all major and minor test hardware required for the prime contractors development test program. It includes boilerplates, static test vehicles, compatibility test unit, electronic systems test unit, thermal qualification test vehicle, and all miscellaneous test parts. Each subsystem cost is estimated as a function of first unit cost and the quantity of test units required. All subsystems except the thermal/structure group are estimated at 100 percent of first unit cost for each test unit that includes the subsystem.

The structural cost is estimated based on the following percentage factors.

Type Test Unit	Percent First Unit Cost for each unit fabricated
Boilerplate	10
ESTU	30
CTU	30
Static	70
Thermal Qual	70

In addition to the above one equivalent test unit is included to account for miscellaneous structural test components.

Appendix C presents only a typical equation since each one would be repetitious.

6.2.16.3 Boosted Flight Test Hardware - The boosted flight test hardware is production flight hardware and is calculated from first unit cost using the cummulative average learning curves presented in Table 6-7.

6.2.17 Mockups - The cost categories for mockups include engineering design, production fabrication, and materials. The mockups for the Gemini program were continually changed throughout the program to reflect the configuration of each spacecraft. Therefore, the cost presents a trend that is not indicative of a normal program. However, usable data can be derived from the cost history. Engineering design for mockups through June of 1964 is considered reasonable for the design cost. The materials cost at $1.00 per manhour is further substantiated by the S-IVB history.

Engineering design for mockups has been formulated in terms of total spacecraft dry weight.

Production fabrication cost is based on the S-IVB history which indicates a cost of about 20% of first unit cost. This is consistent with past Aircraft history.

The materials cost is estimated at $1.00 per production manhour.

6.3 Investment Phase - The investment phase includes the total hardware procurement cost required for the support of the operational phase. The hardware cost is estimated by cost category and spacecraft subsystem as a function of first unit cost and the applicable learning curve. See Section 6.2.16 for the learning curves employed. The investment phase hardware cost is calculated as a follow-on procurement cost to the RDT&E boosted flight test hardware.

i.e.

$$C = T_1 \left(QI1^b - QF1^b\right)$$

where

C = Investment Phase procurement cost of a subsystem

T_1 = First unit cost of that subsystem

QI = Quantity of investment phase hardware plus quantity of RDT&E boosted flight hardware

QF = Quantity of RDT&E boosted flight hardware

b = Applicable learning curve exponent

Table 6-7

LEARNING CURVES				
	ENTRY VEHICLE		MISSION MODULE	
	PRIME CONTRACTOR LABOR	MAT'L.,CFE SUBCONTRACT	PRIME CONTRACTOR LABOR	MAT'L., CFE SUBCONTRACT
Sustaining Engineering	70	--	70	--
Sustaining Tooling	77	--	77	--
Thermal Structure				
Crew Section	85	90	--	--
Cargo/Propulsion Section	90	90	90	90
Simple Adapter	--	--	90	90
Aero Control Surfaces	85	90	--	--
Thermal Protection	85	90	--	--
Landing Gear	85	90	--	--
Launch Escape Tower	90	90	--	--
Inflatable Aero Devices	85	90	--	--
Power Supply & Ordnance	85	90	85	90
ECLS	85	90	85	90
Avionics	85	90	85	90
Propulsion	85	--	85	--
Engines	--	95	--	95
Tanks	--	90	--	90
LVM	--	90	--	90
Final Assembly & Checkout	85	90	85	90

6.4 Operational Phase CER Equations - The operational CER equations were developed from the analysis of the Gemini launch operations program discussed in Volume II, Book 2 and studies performed by MDAC and other contractors for the NASA and the USAF. The development phase and the operational phase CERs were defined by considering the number of development launches (QF2) and the total number of launches (QI2). CERs were developed for both manpower costs and material cost for all cost items except Mission Control Support and Factory Technical Support which has only labor costs and Recovery Operations Costs which are in total only. No further breakdown of these costs was attenpted due to a lack of data upon which to base such a breakdown. Various switches were required to accommodate user input options and vehicle configuration variations.

The operational CER's have been developed assuming a log linear unit cost curve. The total costs have the form $C = a \sum_{1}^{N} j^{b}$ which differs from the cum-average form used in the bulk of the CER's. A cum average curve can be approximated by $C = a(\frac{1}{1+b})\, N^{b+1}$ where "a" and "b" are the unit curve coefficients. This will permit the reader to translate these operational CER's into the other form if he so desires.

6.4.1 Launch Operations - These equations are the summation of six subcategories plus propellant costs. The six subcategories are: Industrial Area Activities, Radar Calibration and Pyro Buildup, On-pad Assembly, On-pad Testing, Countdown, and Miscellaneous Activities. The manpower terms are sensitive to the vehicle size and economic factors (through the labor rate). The material terms are the propellant cost which are sensitive to boil-off or utilization and economic factors, and are responsive to vehicle size through the propellant weight terms. These propellant costs are for the spacecraft only, and do not include the launch vehicle propellants which are considered in the launch vehicle cost model.

Labor Costs - The launch operations labor cost can be estimated by following equation:

$$OP1 = KLRS[\{ \sum_{QF2}^{10} (18{,}590N^{-.400} + 10{,}094N^{-.349} +$$

$$+ 19{,}373N^{-.025} + 12{,}160\,N^{-.197} + 13{,}831\,N^{-.238} +$$

$$45{,}325^{-1.006} + \sum_{11}^{QI2} (8{,}390 + \frac{35{,}874}{N} +$$

$$19{,}373\,N^{-.025} + \frac{10^4}{1.45870 - \frac{1.62251}{N}} + \frac{10^4}{1.44312 - \frac{1.84469}{N}}\ \frac{10^4}{3.67781 - \frac{13.3646}{N}}\}$$

$$\{(2.11 \times 10^{-4})\ (TSC)^{.485}\} + \{1.74 \times 10^5\ (\frac{QI2 - QF2}{PL})^{-.583}\ (QI2\text{-}QF2)\ (USP)\}]$$

where:

OP1	=	Launch Operations Labor Costs
QF2	=	Number of Development Launches
N	=	Number of Launch Attempts
TSC	=	First Unit Cost (structure + subsystem for E/V and M/M)
PL	=	Operational Program Life in Years (first to last launch)
KLRS	=	Composite Labor Rate
Q12	=	Total Number of Launches
USP	=	Integral Upper Stage Propulsion Switch Reuse ≤ 3, USP = 0; Reuse ≥ 4, USP = 1

This apparently complex equation can be approximated by the following relationships:

For $N \leq 19$; $OPI \approx [25.2394N^{.754}\ (TSC)^{.485} +$

$$+ 1.74 \times 10^5\ (PL)^{.583}\ (QI2\text{-}QF2)^{.417}\ (USP)](KLRS)$$

For $N \geq 20$; $OPI \approx [(61.5154 + 9.2135N)\ (TSC)^{.485} +$

$$+ 1.74 \times 10^5 (PL)^{.583}\ (QI2\text{-}QF2)^{.417}\ (USP)]\ (KLRS)$$

and a plot of this approximation is shown in figure 6-54. These may help the reader to better understand this CER, but the more exact relationship will be used in the computerized model.

Material Costs - The material costs associated with launch operations are the propellants and gases costs which can be estimated by the following equation :

OMI = [.1182(WLOH) + 1.2825 (WLFH) + .8395(WFOC) + .2310 (WSTO)] [QI2 - QF2] [KMSC]

OML = Launch Operations Material Costs

KMCS = Ecomonic Factor

WLOH = Bulk Weight of O_2/H_2 in Pounds Per Launch

WLFH = Bulk Weight of F_2/H_2 in Pounds Per Launch

WFOC = Bulk Weight of FLOX/CH_4 in Pounds Per Launch

WSTO = Bulk Weight of NTO/A-50 in Pounds Per Launch

The above equation includes boil-off and line loss allowances.

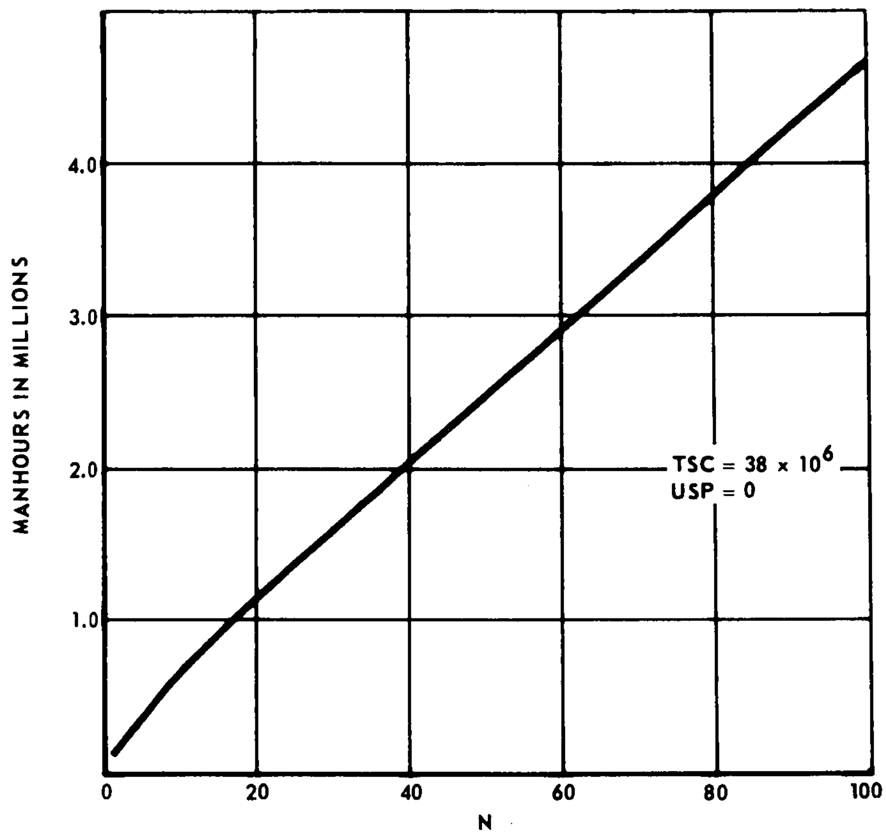
6.4.2 Launch Area Support - The equation is sensitive to vehicle size and program duration. The division between labor and material is less than experienced on the Gemini program, but is representative of the split anticipated in an operational program.

This category provides the sustaining costs associated with a continuing launch operation such as liaison engineering, future planning, repair of government owned equipment, and office forces for documenting and reporting.

Labor Costs - The labor costs are composed of a fixed monthly cost and a per-launch cost term. The following equation estimates the launch area support labor costs:

Figure 6–54

CUMULATIVE LAUNCH OPERATIONS MANHOURS



$$COPLAS = KLRS \left\{ \sum_{QF2}^{QI2} 76{,}301\ N^{-.314} \left[2.11 \times 10^{-4}\ (TSC)^{.485}\right] + \right.$$

$$\left. + (30281)\ (12PL + 11) \right\}$$

where:

COPLAS = Launch Area Support Labor Costs
OF2 = Number of Development Launches
KLRS = Composite Labor Rate
N = Number of Launches
TSC = First Unit Cost (structure + subsystem for E/V & M/MO)
PL = Operational Program Life in Years (first to last launch)
Q12 = Total Number of Attempted Launches

Material Costs - The material costs are handled as 10 percent of the base labor costs which results in the equation:

$$OM2 = \frac{1.6\ COPLAS\ (KMCS)}{KLRS}$$

where:

OM2 = Launch Area Support Material Costs
KMCS = Ecomonic Factor

6.4.3 Mission Control Support Costs - These costs are all manpower costs for services to mission control and mission planning provided by the prime contractor. It is a fixed level staffing.

The estimating relationship for the mission control support labor costs is:

$$OP3 = KLRS\ [(6942\ (12PL + 11)]$$

where:

OP3 = Mission Control Support Labor Costs
KLRS = Composite Labor Rate
PL = Operational Program Duration in Years (first to last launch)

6.4.4 Spacecraft AGE Maintenance Costs - AGE maintenance costs are a function of the number of launches. It is anticipated that a significant learning rate will be experienced, particularly in an operational program which anticipates minimal changes to the spacecraft as the program progresses.

Labor Costs - The labor costs connected with AGE maintenance are estimated by the following equation:

$$COPAM = KLRS \left\{ \sum_{QF2}^{QI2} 162251 N^{-.933} \right\}$$

where:

COPAM	=	AGE Maintenance Labor Costs
QI2	=	Total Number of Attempted Launches
QF2	=	Number of Development Launches
KLRS	=	Composite Labor Rate
N	=	Number of Launches

Material Costs - The material costs associated with AGE maintenance are assumed to be 10% per year of the base labor costs. The equation is:

$$OM4 = \frac{(1.6PL)(COPAM)(KMCS)}{(KLRS)}$$

where:

OM4	=	AGE Maintenance Material Costs
KMCS	=	Economic esclation Factor
PL	=	Operational Program Duration in Years (first to last launch)

6.4.5 Spacecraft Launch Facilities Maintenance Costs - These costs are sensitive to the size of the vehicle and the number of launches. As with AGE maintenance, a high learning rate is anticipated.

Labor Costs - The facilities maintenance labor costs are estimated by this equation:

$$COPFM = KLRS \sum_{QF2}^{QI2} 38218 \; N^{-.831} \; [2.11 \times 10^{-4} (TSC)^{.485}]$$

where:

COPFM	=	Facilities Maintenance Labor Costs
KLRS	=	Composite Labor Rate
QF2	=	Number of Development Launches
QI2	=	Total Number of Attempted Launches
N	=	Number of Launches
TSC	=	First Unit Cost (structure + subsystem for E/V & M/M)

Material Costs - The material costs associated with the facilities maintenance are estimated to be 1% per year of the base labor costs. The equation used is:

$$\text{OM5} = \frac{(1.16\text{PL})(\text{COPFM})(\text{KMCS})}{\text{KLRS}}$$

where:

OM5 = Facilities Maintenance Material Costs
KMCS = Economic Factor
PL = Operational Program Duration in Years (first to last launch)

6.4.6 Recovery Operations Costs - These are costs to the customer rather than to the prime contractor, but they are a part of the Cost Element Structure and are included here as total costs. The CER to be used in the cost model is:

$$\begin{aligned}\text{06} = {} & [\{(1\text{-VLM})\ [(1\text{-E2S})(168{,}000) + (\text{E2S})(\text{NS})(84{,}000)]\ + \\ & + (\text{VLM})\ (\text{LLM})\ [(1\text{-E2S})(240{,}000) + (\text{E2S})(\text{NS})(120{,}000)]\ + \\ & + 200{,}000 + (\text{VLM})(42{,}000) + (1\text{-LLM})\ (528{,}000)\}\ (\text{QI2} - \text{QF2})\ + \\ & \{(1\text{-VLM})\ [(1\text{-E2S})(46{,}166) + (\text{E2S})(\text{NS})(21{,}500)]\ + \\ & (\text{VLM})\ (\text{LLM})\ [(1\text{-E2S})(42{,}500) + (\text{E2S})(\text{NS})(19{,}333)]\ + \\ & (1\text{-LLM})\ (115{,}500)\}\ (12\ \text{PL} + 3)\ ]\ \ (\text{KECON})\end{aligned}$$

where:

06 = Recovery Operation Costs
VLM = Vertical Landing Mode Switch 0 = No, 1 = Yes
E2S = Existing Site Network Switch 0 = No, 1 = Yes
LLM = Land Landing Mode Switch 0 = No, 1 = Yes
NS = Number of Existing Sites (2 or more)
QF2 = Number of Development Launches
QI2 = Total Number of Attempted Operational Launches
KECON = Economic Factor
PL = Program Duration in Years (first to last launch)

6.4.7 Recertification Costs - This is the cost of the refurbishment operations. The developed CER's are sensitive to the type of thermal protection, the size of the vehicle, the number of engines if the vehicle has integral upper stage propulsion engines, and the hot firing test requirements.

Labor Costs - This CER assumes that, whether the recertification is carried on at the factory or in a newly established facility, the production labor rate would apply. The CER is:

$$OP7 = [(KPROD)(1.40)]\ \{[31.2\ (SWTPA) + 19.2\ (SWTPR)]\ [2.11 \times 10^{-4}\ (TSC)^{.485}] \sum_{NR=1}^{NR\leq 100} NR^{-.415} + \sum_{NR=101}^{NR} NR^{-.234}$$

$$+ [15,528\ (BAL) + 16,299\ (1-BAL) + 3600\ (NE)] \sum_{NR=1}^{NR} NR^{-.234} +$$

$$[(1-.8TDS)(AGEF)(21060 + 1375\ NE) + 12,000\ (HFT)] \sum_{NR=1}^{NR} NR^{-.152}\}$$

where:

OP7	=	Recertification Labor Costs
SWTPA	=	Ablative Total Panel Area - Sq. Ft.
SWTPR	=	Radiative Total Panel Area - Sq. Ft.
TSC	=	First Unit Cost (structure + subsystem for E/V & M/M)
NR	=	Number of Recertifications
NPROD	=	Production Labor Rate
BAL	=	Configuration I Switch 0 = No, 1 = Yes
TDS	=	Test Deletion Switch REFPC = 3, TDS = 1; REFPC ≠ 3, TDS = 0
AGEF	=	AGE Factor (one of four values)
NE	=	Number of Engines in Integral Propulsion
HFT	=	Hot Firing Test Switch 0 = No, 1 = Yes

Material Costs - The CER for material costs associated with recertification is:

$$OM7 = [(.165)\ (CMSSE) + (.22)\ (CPSGE + CMSGE)]\ (KMCS) \sum_{NR=1}^{NR} NR^{-.152}$$

where:

OM7	=	Recertification Material Costs
CMSSE	=	First Unit Subsystem Material Costs of the Entry Vehicle
CMSGE	=	First Unit Material Costs of E/V Thermal Structure Group
CPSGE	=	First Unit Production Costs of E/V Thermal/Structure Group
KMCS	=	Economic Factor

6.4.8 Transportation Costs - These costs are a subcontracted cost or material cost dependent upon the transportation mode. The CER is:

$$\text{OM8} = \{(N)\ [20{,}000\ (ATS) + 14000\ (LTS) + 115{,}000\ (BTS)] + (NR)\ [40{,}000\ (ATS) + 21{,}000\ (LTS) + 139{,}000\ (BTS)]\}\ (KMCS)$$

where:

OM8 = Transportation Costs
N = Number of Operational Units Procured
NR = Number of Refurbishments
ATS = Air Transportation Switch 0 = No, 1 = Yes
LTS = Land Transportation Switch 0 = No, 1 = Yes
BTS = Barge Transportation Switch 0 = No, 1 = Yes
KMCS = Economic Factor

6.4.9 Factory Technical Support - During the operational phase of any program, there is a sustaining engineering and sustaining tooling effort required at the factory to support the operational phase. This is a labor cost only. There is little data upon which to base any estimating relationships. Experience in missile programs indicates that the sustaining force size is influenced by the cost of the program -- the higher the program cost, the larger the sustaining manpower. The Gemini and Saturn programs do not offer a good data base because of the nature of the programs, both had artifically high manpower levels due to the research nature of the programs.

A study of an advance Big G spacecraft has indicated that this sustaining engineering would average 500 men over 30 months to support a 10 launch program. This spacecraft is similar to the modular ballistic (IB) of this study; however, the program durations of this study are much longer and hence the average force would be lower. A limited amount of data indicates a 80% improvement factor might be expected. The labor rate and the size/complexity factor used before are included in the CER which is:

$$\text{OP9} = 23.632\ (KLRS)\ (TSC)^{.485}\ (PL)^{.678}$$

OP 9 = Factory Technical Support Labor Cost
KLRS = Composite Labor Rate
TSC = First Unit Cost
PL = Operational Program Duration in Years (first to last launch)

7. Launch Vehicle Cost Estimating Relationships - The cost optimization program has been designed such that launch vehicle performance, weight and cost sub-routines can be inserted at a later date, permitting optimization of the total flight system. The development of detailed launch vehicle cost analysis sub-routines was not included in this study due to funding limitations and a desire to concentrate on the spacecraft segment of the system. Consequently, the launch vehicle analysis consisted of formulating gross cost-performance relationships for one or more concepts within each launch vehicle class.

7.1 Study Scope - The scope of the analysis is summarized in Table 7-1. The concepts within the vehicle classes were chosen on the basis of data availability and generally represent state of the art in technology. Analyses involving concepts other than those included here can be accomplished by adding similar cost performance relationships to the present optimization program. The "solid boosted/liquid" concept consists of an expendable two staged tandem vehicle employing 156-inch diameter solid rocket motors (SRM) first stage and a cryogenic (LO_2/LH_2) upper stage for the small payload sizes (Ref 7-1). As payload requirements increase, additional SRM's (to a maximum of 4) are added to and zero staged from the core first stage. Previous studies of this concept have yielded a payload capability range of from 10,000 to 150,000 pounds as indicated in Table 7-1. The second two stage all expendable concept is a LO_2/RP first - LO_2/LH_2 second stage vehicle as represented by the current Saturn family of launch vehicles. In fact, three Saturn point designs (uprated Saturn I, S-IC/S-IVB, and S-IC/S-II) were used to estimate the cost-performance characteristics of this concept, which results in the indicated range of thrown weight capabilities. For the purposes of this study these two concepts would be used with the A, B and C configurations of each spacecraft concept which have an orbital thrown weight requirement of from 40,000 to 300,000 pounds.

For those combination spacecraft/upper stage concepts (i.e., D, E and F configurations) both expendable (solid and liquid propulsion) and reusable first stage concepts were examined. The solid propellant expendable system consists of a 260-inch diameter SRM similar to that currently proposed for the solid boosted S-IVB vehicle (MLV-SAT-IB-5) (Ref 7-2), and parametric

Table 7-1

LAUNCH VEHICLE REQUIREMENTS SUMMARY

LAUNCH VEHICLE CLASS	LAUNCH VEHICLE CONCEPT	THROWN WEIGHT CAPABILITY (LB.)	USED FOR SPACECRAFT CONFIGURATIONS	THROWN WEIGHT REQUIREMENT (LB.)
Expendable First and Second Stages	Solid/Liquid (LO_2/LH_2)	10K-150K-ETR (i = 28.5)	IA, IB, IC, IIA, IIB, & IIC	40K to 300K(1)
	Liquid/Liquid ($LO_2/RP-LO_2/LH_2$)	40K-250K-ETR (i = 28.5)		
Expendable First Stage	Solid (260" Dia.)	100K-1600K - ETR	ID, IE, IID, & IIE	150K to 1600K(2)
	Liquid (LO_2/RP)(3)	175K ETR(2)		
Reusable First Stage	VTOHL (LO_2/LH_2)	130K-1050K(2)	IIF	150K to 1600K(2)

1. 100 N. Mi. Circular Orbit - 50° (Nominal) Inclination from ETR, 70° & 90° from WTR.
2. To a Staging Velocity of 10,600 FPS.
3. No Parametric Data Provided. Single Point Corresponding to Uprated Saturn I First Stage Evaluated.

data is included over the required design range. The expendable liquid first stage corresponds to the Saturn I first stage and was evaluated for the single design point. The reusable first stage is based on a previous study (Ref. 7-3) and consists of a manned lifting body vertical take-off horizontal lander, employing a high pressure LO_2/LH_2 propulsion system.

7.2 Cost Estimates - The cost data for all concepts were estimated by use of two previously developed cost models (Ref. 7-1 and 7-3). In order to put these data into a form appropriate for use in the cost optimization program, summary expressions were formulated. The cost estimating relationships are given in Table 7-2 and plotted in Figures 7-1 thru 7-12 for each system in terms of its development, program average investment and program average operations cost. The development cost includes all elements required to bring a system from a contract definition phase through system qualifications, and in all cases includes a five flight vehicle test program. For the reusable case, these flight vehicles are also utilized to support the operational phase of the program, which results in no additional investment costs for operational launch rates less than 30 per year (for the assumed stage turnaround time of 64 calendar days.)

The investment cost category is the same as that employed for the spacecraft portion of the system and includes the manufacturing cost and sustaining engineering associated with the production of all flight hardware used in the operational phase of the program. The operations category costs include spares, propellants, transportation, launch operations, facility and equipment maintenance, and recovery and refurbishment costs for the reusable system. Due to the relatively mild operating environment of the reusable first stage, a unit refurbishment cost of 1% of average procurement cost was used for annual launch rates of 6 and greater. This percentage was increased for lower rates to a maximum of 2% at two per year to account for the reduction in crew utilization at the lower rates.

In addition to the above cost elements "Program Office Management" which includes all customer related support costs for the launch vehicle segment of the system is required. The relationships to be used for this element are as follows:

Table 7-2

LAUNCH VEHICLE COST PERFORMANCE RELATIONSHIPS

	LAUNCH VEHICLE CONCEPT	DEVELOPMENT COST	PROGRAM AVERAGE INVESTMENT COST	PROGRAM AVERAGE OPERATIONS COST
COMPLETE BOOST SYSTEM	SOLID/LIQUID (LO_2/LH_2) $10K < W_T < 150\ K$	$C_{DEV} = 450 + 2.26 \times 10^{-3}\ W_T^{2.33}$	$\bar{C}_{INV} = 0.155\, k_L R^{-0.495}\ (.82\ W_T\ 1.25R^{0.058})$ $k_L = 1.14 - 0.14\ L_p$ FOR $L_p < 10$ $= 1.28 - 0.028\ L_p$ FOR $L_p < 10$ $2 \leq R \leq 24$	$\bar{C}_{OP} = 15.8R^{-0.812} + \alpha\ W_T$ $\alpha = 0.308^{-0.99}$ FOR $2 \leq R \leq 6$ $= 0.10455^{-0.385}$ FOR $6 \leq R \leq 24$
	LIQUID (LO_2/RP)/ LIQUID (LO_2/LE_2) $20K < W_T < 350K$	$C_{DEV} = 719\ W_T^{0.275}$	$\bar{C}_{INV} = 9.82 k_L R^{-0.276}\ W_T^{0.43}$ $k_L = 1.0$ FOR $L_p = 10$ $= 1.28 - .028\ L_p$ FOR $L_p < 10$ $2 \leq R \leq 24$	$\bar{C}_{OP} = \alpha\ W_T^{0.314}$ $\alpha = 5.7R^{-0.47}$ FOR $6 \leq R \leq 24$ $= 9.12\ R^{-0.73}$ FOR $2 \leq R \leq 6$
FIRST STAGE ONLY	EXPENDABLE 260" DIA SOLID $100K < W_T < 1{,}800K$ $9K < V_S < 15K$	$C_{DEV} = 34.8\, W_T^{0.466} e^{(2.58 \times 10^{-6} V_S^{4.5})}$	$\bar{C}_{INV} = 0.0145\ e^{(1.84 \times 10^5\ V_S^4)(320R^{-0.241} + W_T R^{-0.206})}$ $2 \leq R \leq 24$	$\bar{C}_{OP} = 3.52\ e^{(4.12 \times 10^{-5} V_S^{3.6})} R^{-1.08} \times W_T (0.404 R^{0.0866})$ $2 \leq R \leq 24$
	EXPENDABLE LIQUID (LO_2/RP) $W_T = 175{,}000$ LB $V = 10{,}600$ FPS	$C_{DEV} = 1{,}315$	$\bar{C}_{INV} = 33.1 k_L\ R^{-0.306}$ $k_L = 1.0$ FOR $L_p \geq 10$ $= 1.2 - .02 L_p$ FOR $L_p < 10$ $2 \leq R \leq 24$	$\bar{C}_{OP} = 27.4R^{0.775}$ $2 \leq R \leq 24$
	REUSABLE VTOHL (LO_2/LH_2) $100\ K < W_T < 1{,}800K$ $V_S = 10{,}600$ FPS	$C_{DEV} = 1500 + 7.8\ W_T^{0.86}$	NONE FOR $R < 30$	$\bar{C}_{OP} = 12.85R^{-0.586} + \alpha\ W_T^{\beta}$ $\alpha = 1.115R^{-1.9}$ FOR $2 \leq R \leq 6$ $= 0.0467R^{-0.131}$ FOR $6 \leq R \leq 24$ $\beta = 0.6R^{0.186}$ FOR $2 \leq R < 6$ $= 0.9R^{-0.0424}$ FOR $6 \leq R \leq 24$

C = COST IN MILLIONS OF 1969 DOLLARS
W_T = THROWN WEIGHT CAPABILITY IN THOUSANDS OF POUNDS (DUE EAST ETR LAUNCH, $i = 28.5°$)
R = ANNUAL LAUNCH RATE
L_P = LENGTH OF OPERATIONAL PROGRAM (YEARS)
V_S = STAGING VELOCITY IN THOUSANDS OF FT/SEC

Figure 7–1

DEVELOPMENT COST TRENDS – LIQUID/LIQUID AND SOLID/LIQUID LAUNCH VEHICLE CONCEPTS
(1969 DOLLARS)

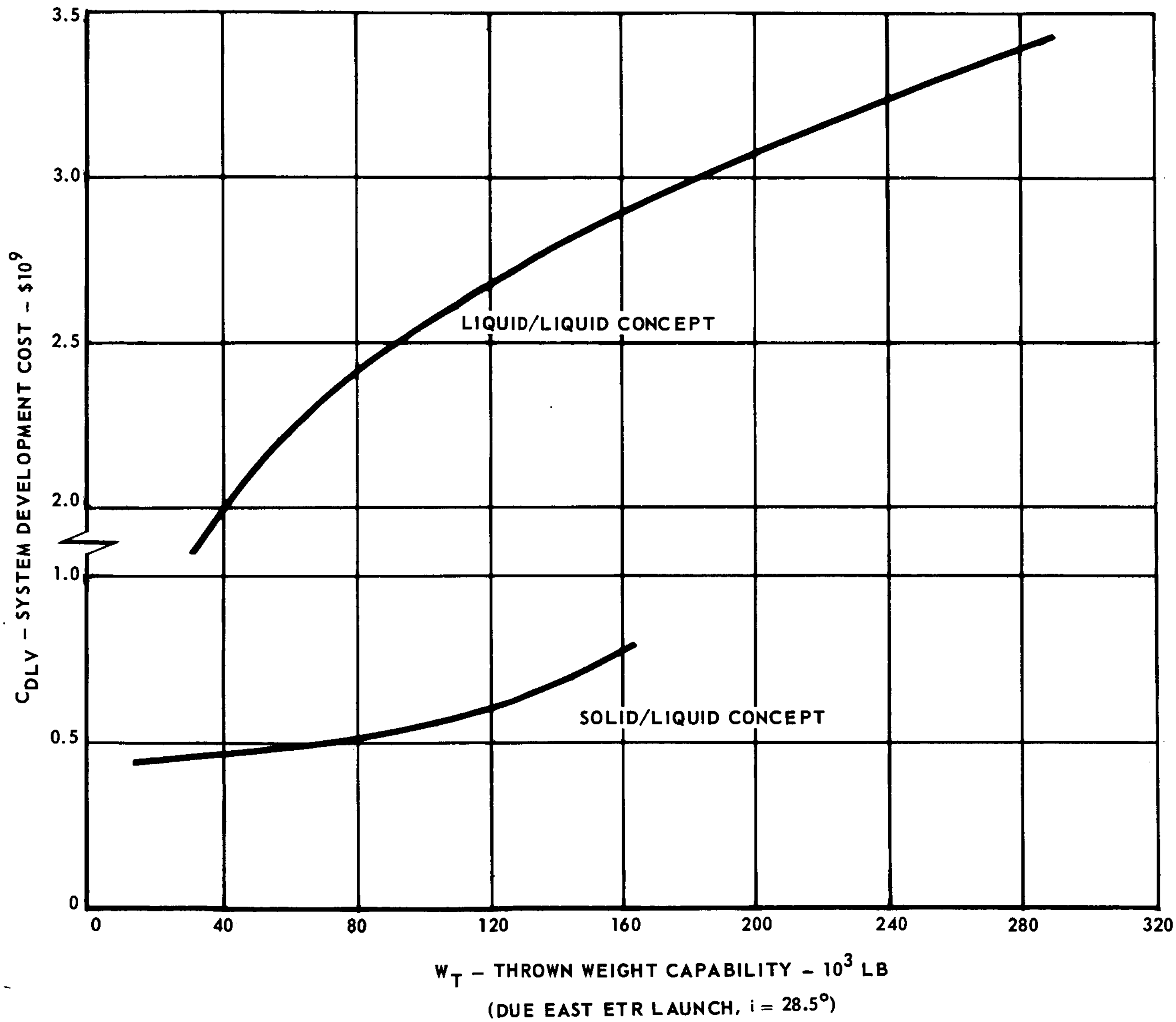


Figure 7–2

INVESTMENT COST TRENDS – SOLID/LIQUID L.V. CONCEPT

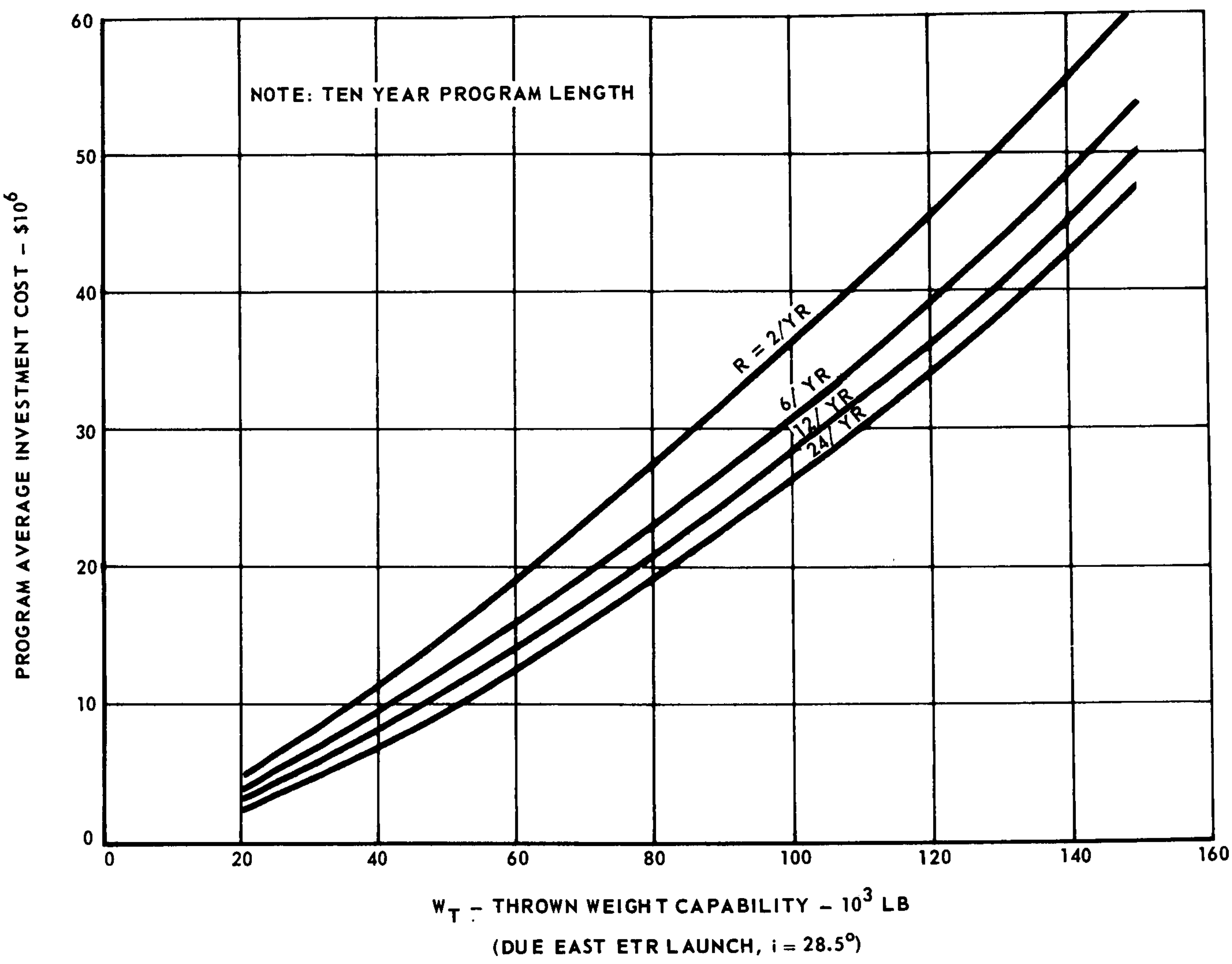
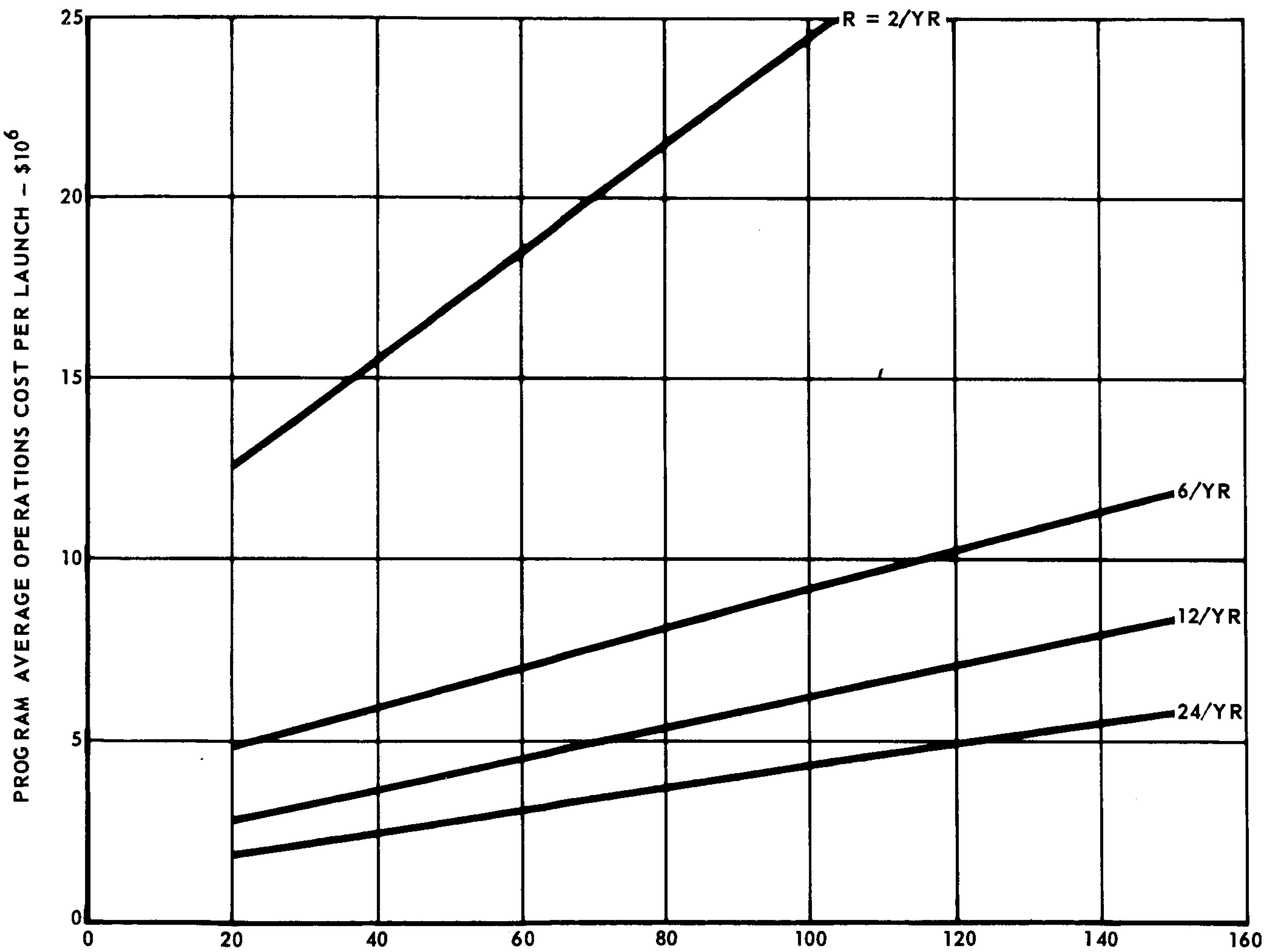


Figure 7-3

OPERATIONAL COST TRENDS – SOLID/LIQUID L.V. CONCEPT
(1969 DOLLARS)



W_T – THROWN WEIGHT CAPABILITY – 10^3 LB
(DUE EAST ETR LAUNCH, i = 28.5°)

Figure 7-4

INVESTMENT COST TRENDS – LIQUID/LIQUID LAUNCH VEHICLE CONCEPT
(1969 DOLLARS)

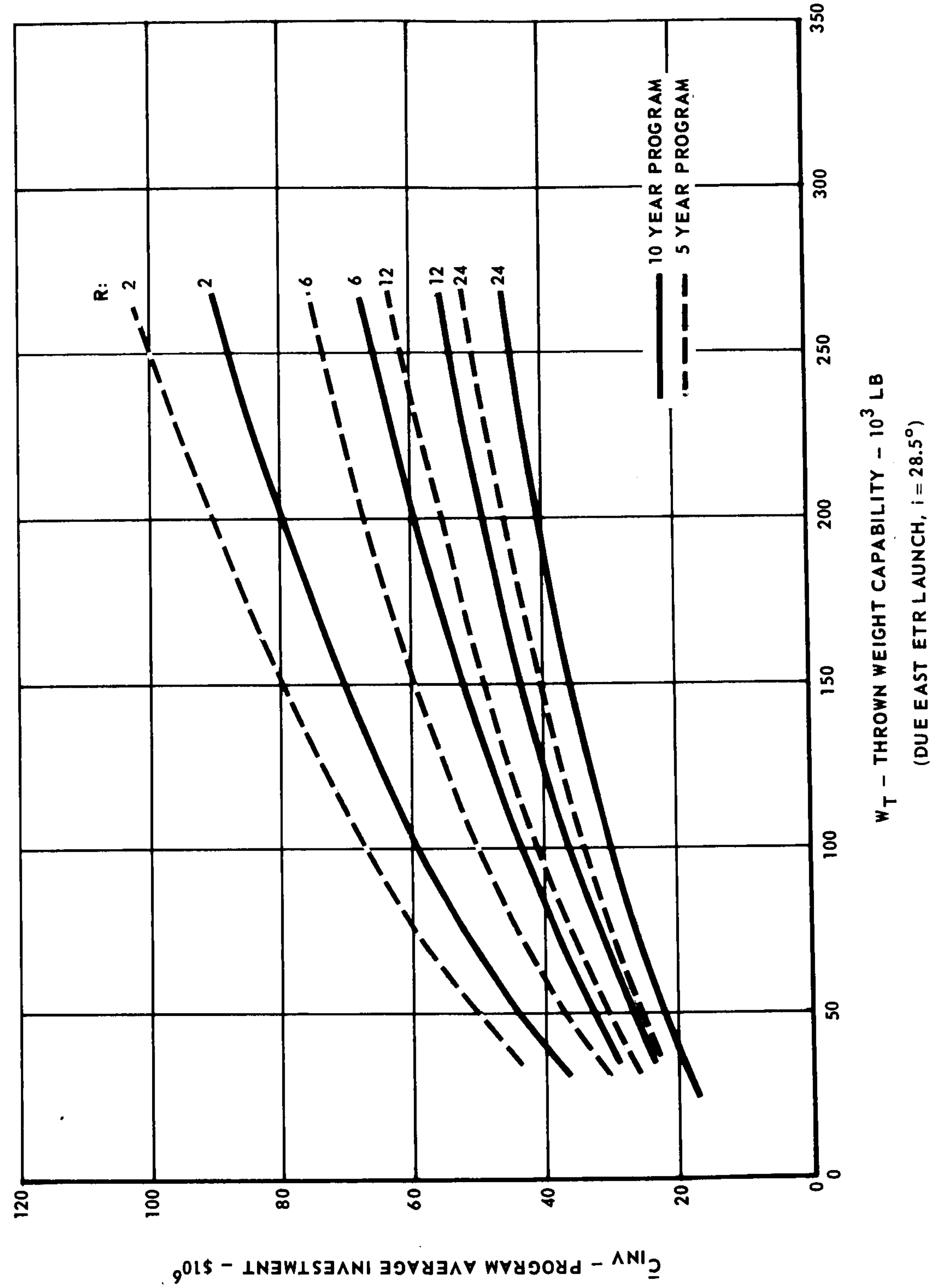


Figure 7–5

OPERATIONAL COST TRENDS – LIQUID/LIQUID LAUNCH VEHICLE CONCEPT
(1969 DOLLARS)

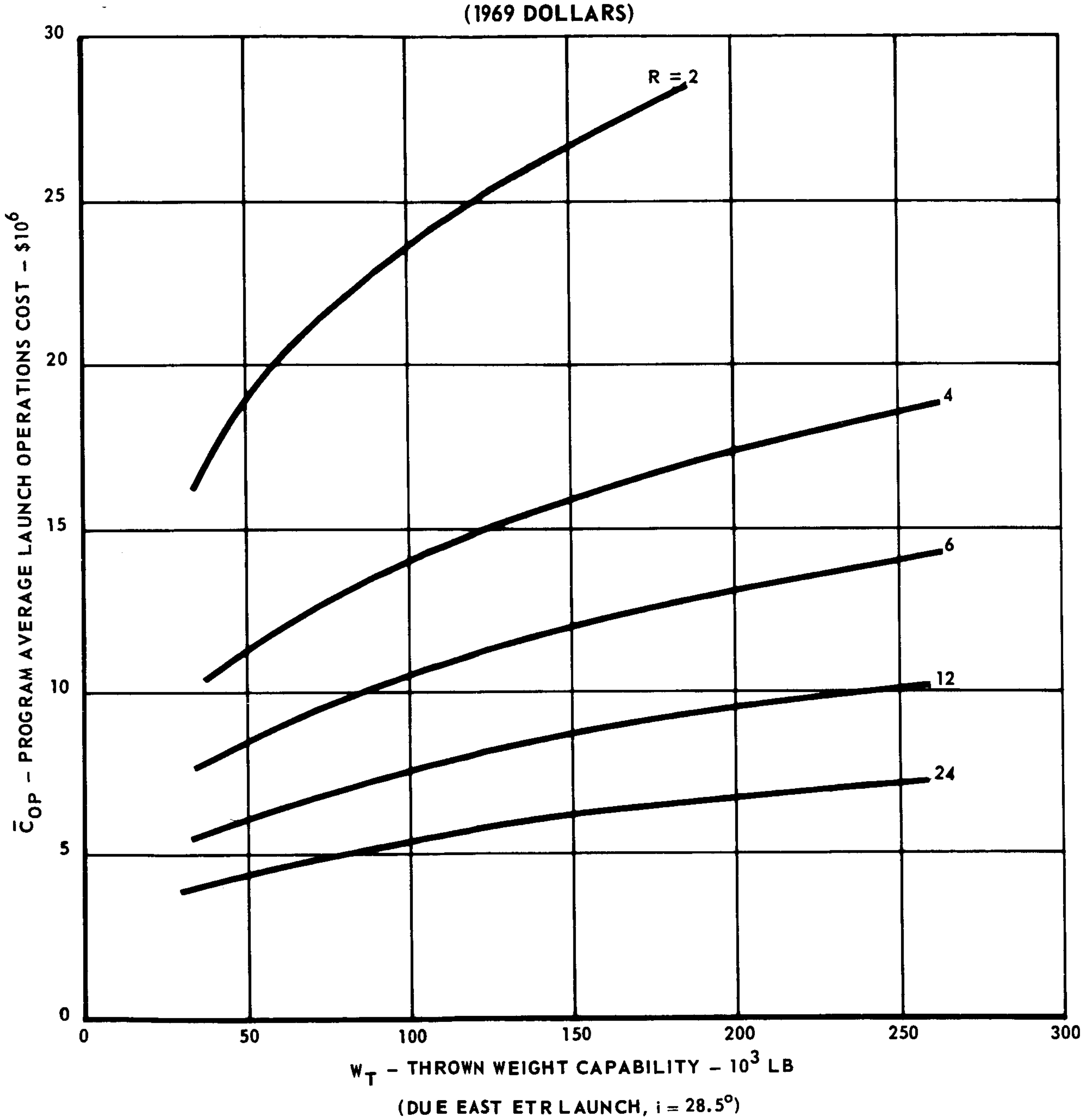
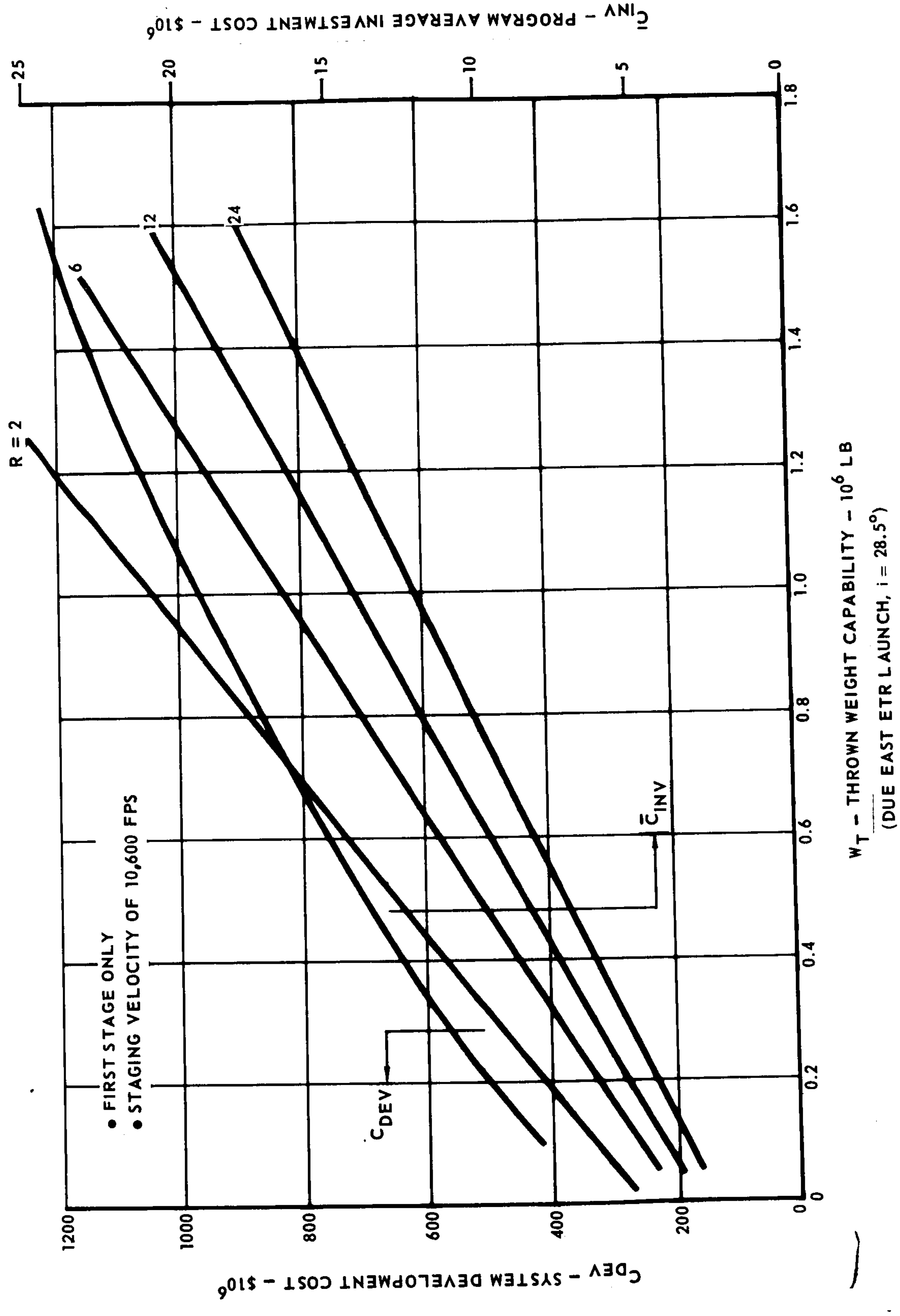


Figure 7-6



COST TRENDS – EXPENDABLE SOLID BOOST STAGE
(1969 DOLLARS)

Figure 7–7

DEVELOPMENT COST TREND – EXPENDABLE SOLID BOOST STAGE
(1969 DOLLARS)

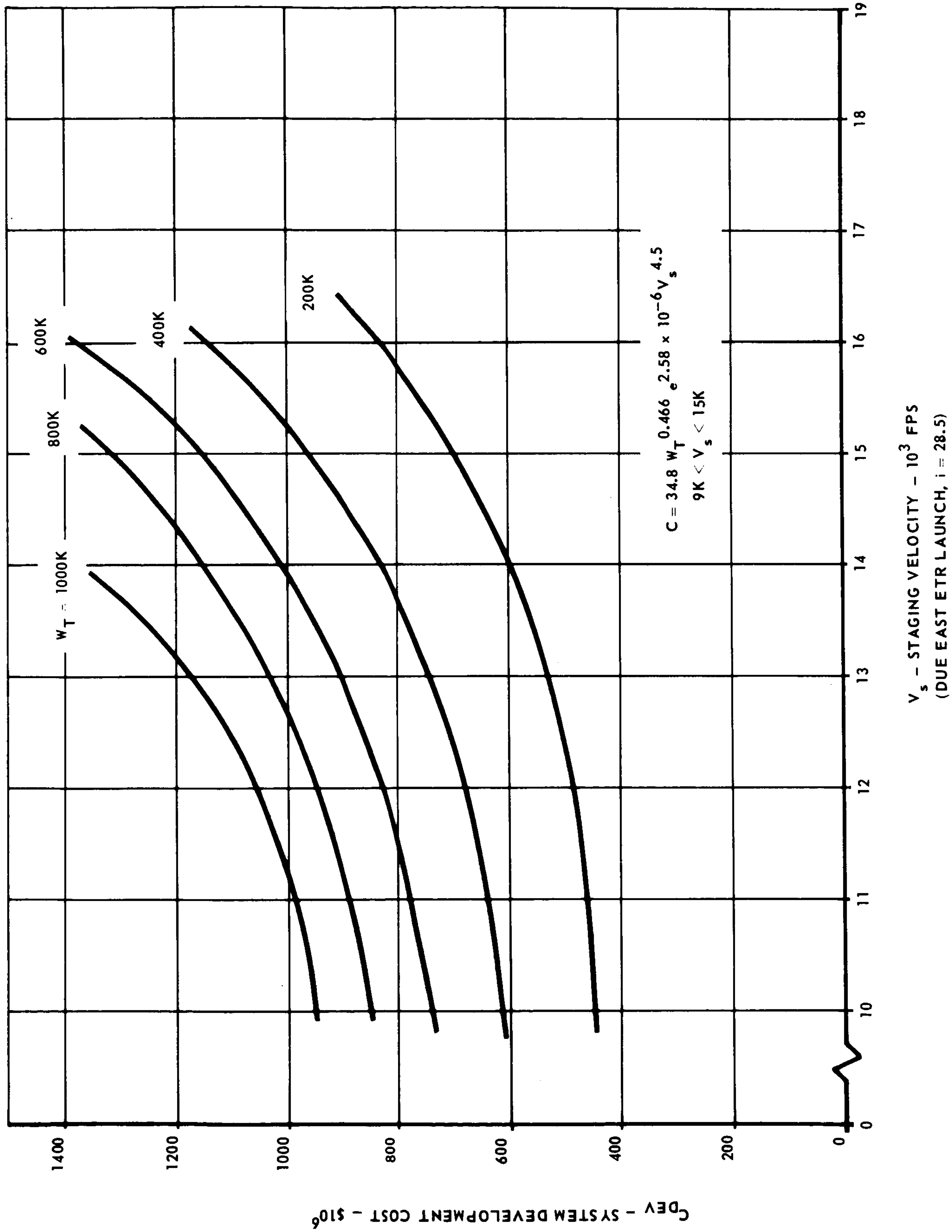


Figure 7–8

INVESTMENT COST TRENDS – EXPENDABLE SOLID BOOST STAGE
(1969 DOLLARS)

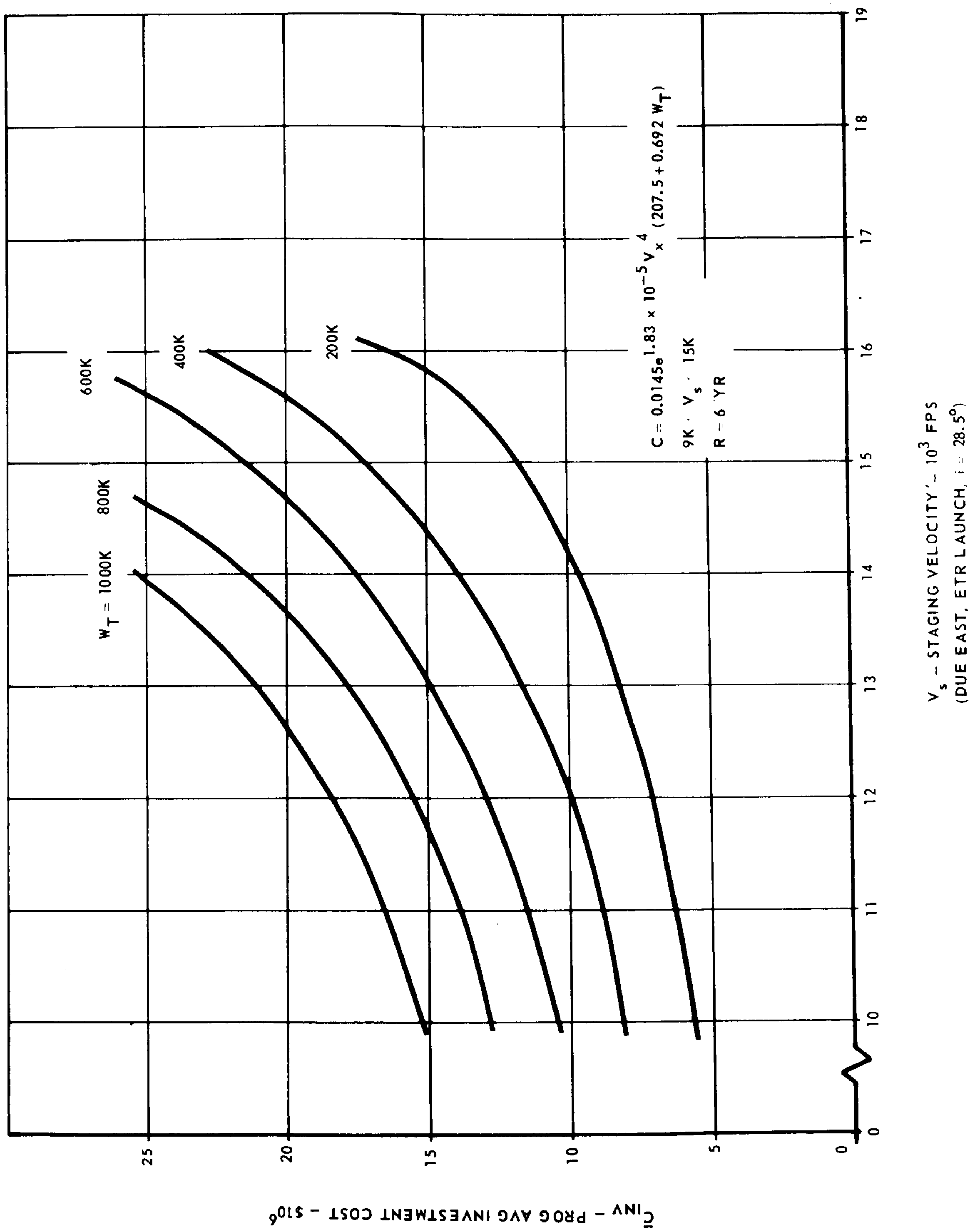


Figure 7-9

OPERATIONS COST TRENDS – EXPENDABLE SOLID BOOST STAGE
(EFFECT OF THROWN WEIGHT)
(1969 DOLLARS)

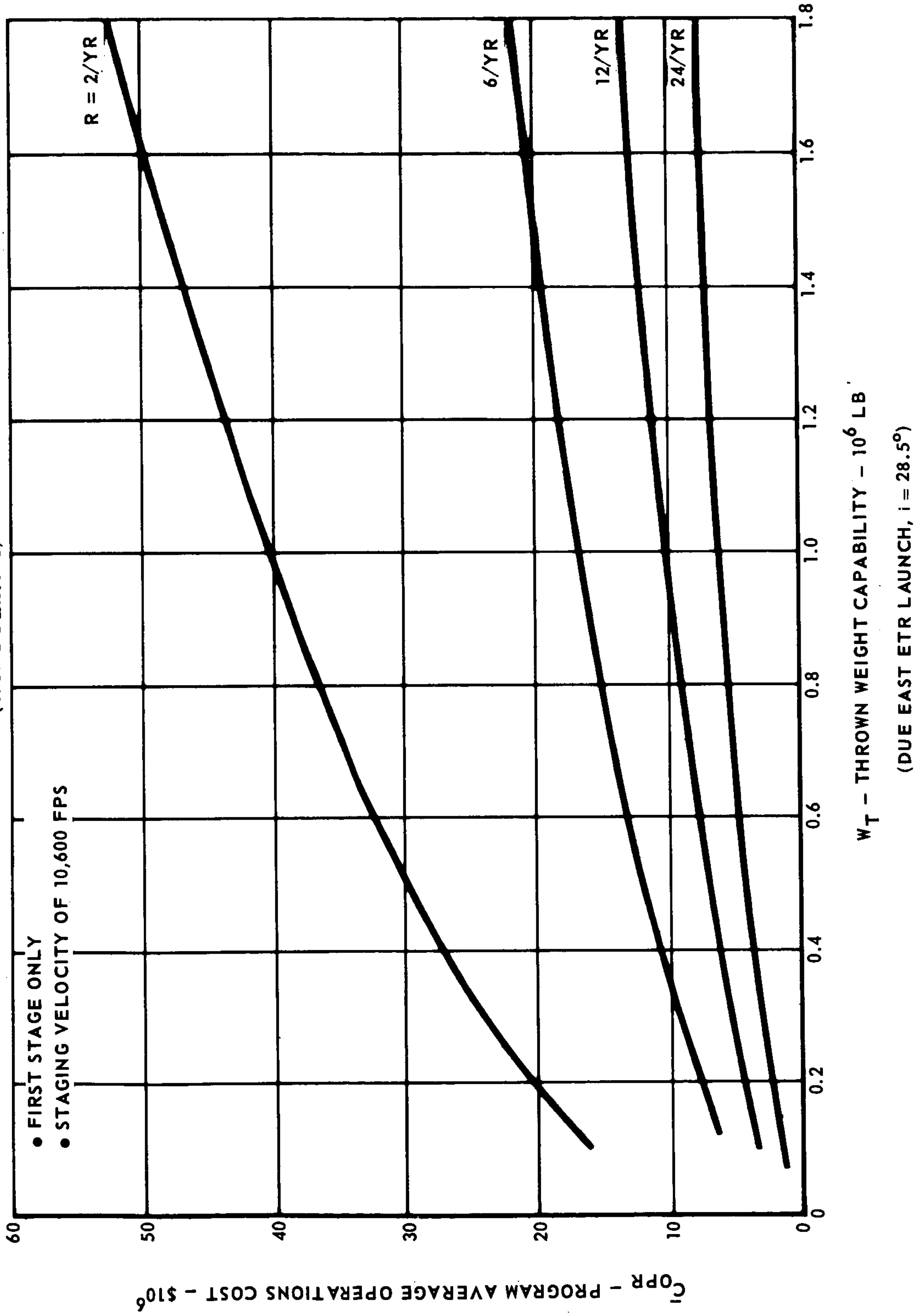


Figure 7-10

OPERATIONS COST TRENDS – EXPENDABLE SOLID BOOST STAGE
(EFFECT OF STAGING VELOCITY)
(1969 DOLLARS)

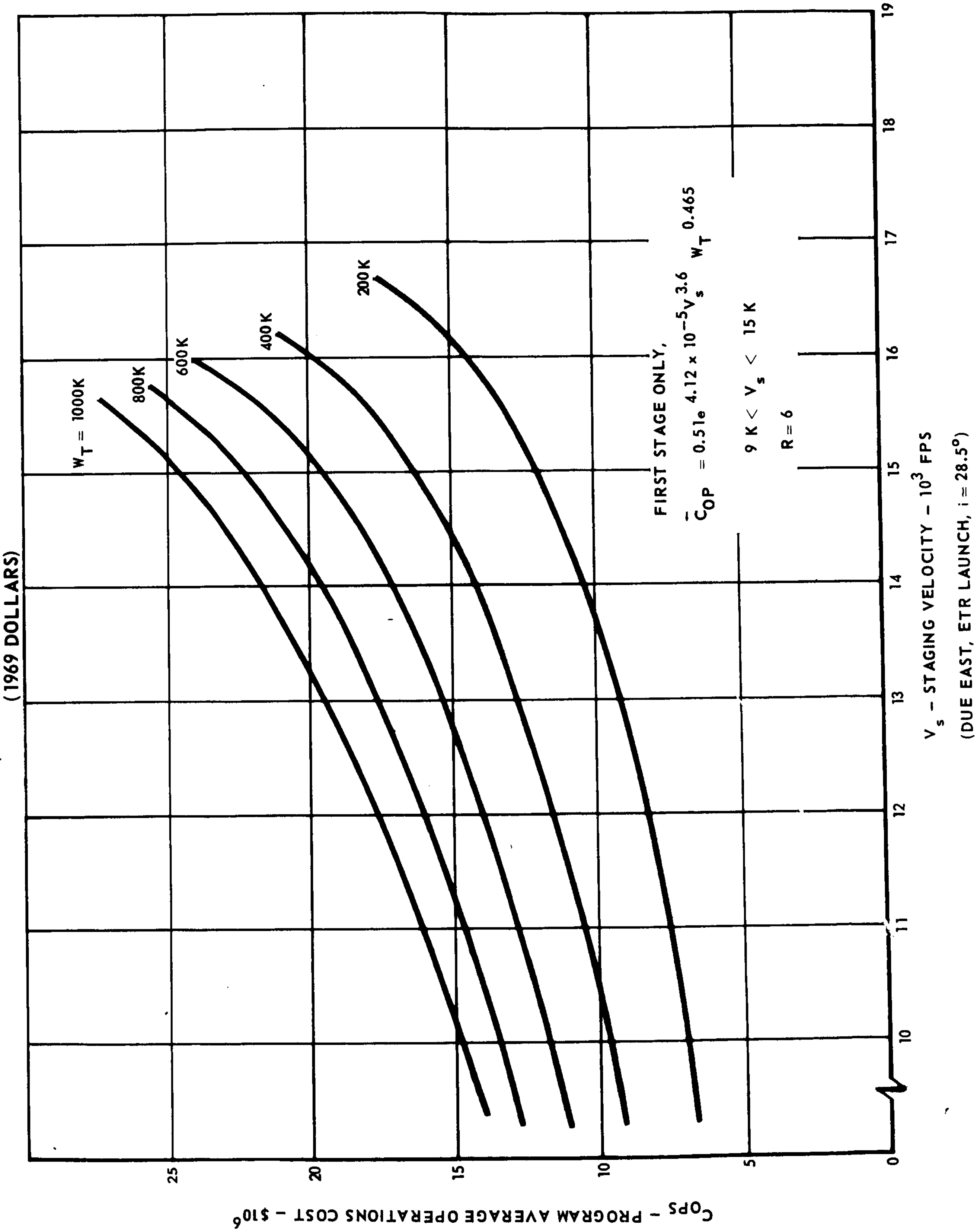


Figure 7-11

EXPENDABLE LIQUID (LO_2/RP) FIRST STAGE
(1969 DOLLARS)

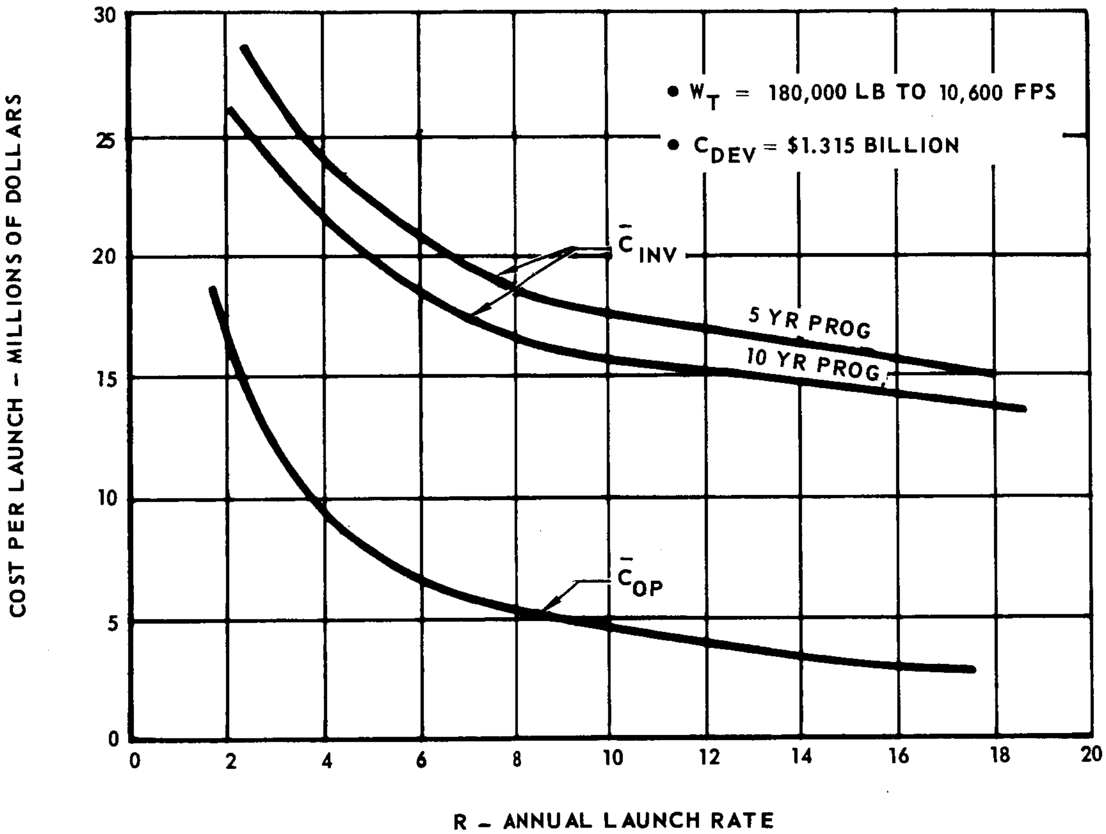
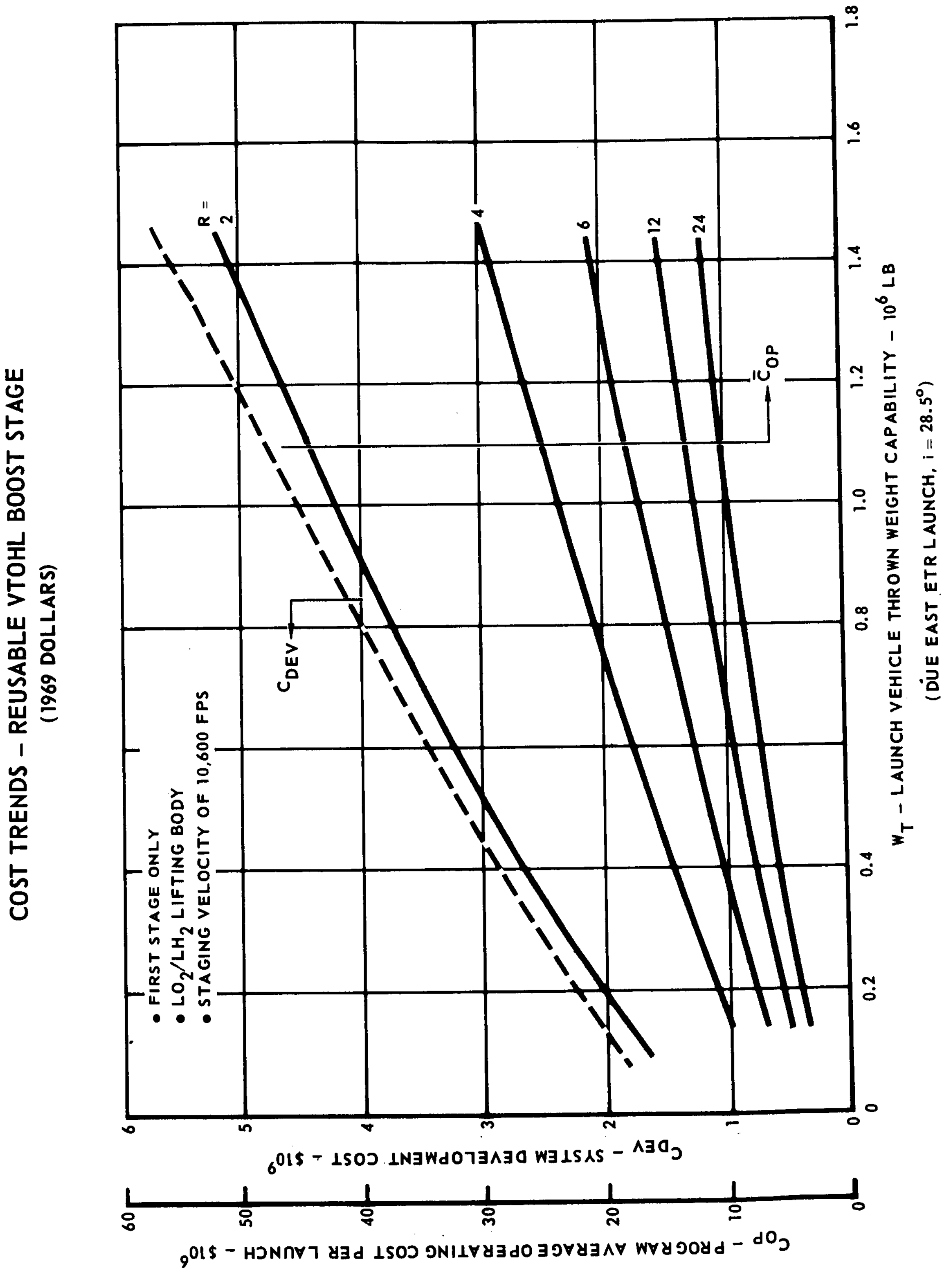


Figure 7–12


COST TRENDS – REUSABLE VTOHL BOOST STAGE
(1969 DOLLARS)
• FIRST STAGE ONLY
• LO_2/LH_2 LIFTING BODY
• STAGING VELOCITY OF 10,600 FPS
R = 2
4
6
12
24
C_{DEV}
$\bar{C}_{OP}$
W_T – LAUNCH VEHICLE THROWN WEIGHT CAPABILITY – 10^6 LB
(DUE EAST ETR LAUNCH, i = 28.5°)
0
0.2
0.4
0.8
1.0
1.2
1.4
1.6
1.8
C_{DEV} – SYSTEM DEVELOPMENT COST – $\$10^9$
0
1
2
3
4
5
6
$\bar{C}_{OP}$ – PROGRAM AVERAGE OPERATING COST PER LAUNCH – $\$10^6$
0
10
20
30
40
50
60

Development Phase: 10% of Program Development Cost.

Operations Phase: $\overline{C}_{POM} = K_n \, (1.25 \times 10^{-3} \, W_T) + 0.44 \; \overline{C}_{OP}$

where: $\overline{C}_{POM}$ = Program Average Cost Per Launch for Program Office Management.

$\overline{C}_{OP}$ = Program Average Operations Cost Per Launch.

K_n = Launch Vehicle Configuration Factor.

= 1.0 for Multistage Launch Vehicles.

= 0.7 for Single Stage Boost Vehicles.

W_T = Thrown Weight Capability (1000 lb)

The operations phase expression assumes a linear relationship with contractor operations cost and varies from 50% for a 50,000 lb. capability (low earth orbit) vehicle to 75% for a 250,000 lb. capability system. These percentage values are representative of published experience on the Saturn program. The resultant cost can be further apportioned in a manner that places 45% in support of investment (hardware procurement) and 55% in support of operations.

All thrown weight capabilities given are for a due East ETR launch ($i = 28.5^{o}$).

Payload variation with launch azimuth is launch vehicle dependent, however the following relationship will provide a reasonable first approximation of the payload capability for the inclinations of interest.

$$W_{T_i} = W_{T_{28.5}} \; e^{.19564(S/N\psi(i)-1)}$$

Where: W_{T_i} = Thrown Weight Capability for Orbital Inclination of i.

$W_{T_{28.5}}$ = Thrown Weight Capability for a Due East ETR Launch ($\psi = 90^{o}$ and $i = 28.5^{o}$)

$\psi(i) = \sin^{-1}(1.139 \cos i)$ for ETR

i = Desired Orbit Inclination

The cost estimating relationships for the expendable liquid first stage and the reusable LO_2/LH_2 first stage were derived for a staging velocity of 10,600 FPS. In order to provide additional analysis flexibility for the program the cost estimating relationships for the solid expendable first stage were based on both thrown weight capability and staging velocity.

REFERENCES

6-1 SAMSO TR-67-4, Vol. V Book I; Multipurpose Reusable Spacecraft Preliminary Design Effort, Cost Analyses, November 1967, Confidential.

7-1 Douglas Report DAC-57990, Improved Launch Vehicles for Spacecraft, April, 1967.

7-2 Douglas Report SM-47043, Saturn IB Improvement Study-Solid First Stage, Feb. 1965.

7-3 Douglas Report DAC-57926, Design Considerations of Reusable Launch Vehicles, Oct. 1966.

APPENDIX A
LIST OF VENDOR COMPANIES

Table A-1 lists the subsystem and component suppliers that responded to requests for design, cost, and reliability data for use in this study. These suppliers, at no cost to the study, provided one or more types of requested data for the type of subsystem listed by their name.

Table A-1.
Suppliers of Design, Cost, and Reliability Data

Supplier	Subsystem
Aerojet-General	Propulsion
Airesearch	Power Supply
Allis-Chalmers	Power Supply
Barnes Engineering	Avionics
Bendix Corporation	Environment Control
Collins Radio Company	Avionics
Hamilton Standard	Environment Control
Honeywell, Inc.	Avionics
IBM	Avionics
Leach, Inc.	Avionics
Marquardt	Propulsion
Motorola	Avionics
Pratt and Whitney Aircraft	Power Supply
Pratt and Whitney Aircraft	Propulsion
Rocketdyne	Propulsion
Spacecraft, Inc.	Avionics
Sundstrand Aviation	Power Supply
TRW, Inc.	Propulsion
Westinghouse	Avionics

APPENDIX B

SYNOPSIS OF GEMINI MISSIONS

Gemini I Mission - The first Gemini mission was an unmanned orbital flight, launched successfully on 8 April 1964. It utilized the first production Geminispacecraft, but did not carry complete flight systems because the mission was primarily a test of structural integrity. Launch occurred at 11:00 am.m. EST; the mission was declared successfully concluded fours and fifty minutes after liftoff. Tracking, however, was continued by the Goddard Space Flight Center until the spacecraft entered on the 64th orbital pass over the southern Atlantic Ocean.

The spacecraft/launch vehicle second stage combination (which was not separated for this mission) was inserted into an orbit having a perigee of 86.6 nautical miles and an apogee of 173 nautical miles. These figures were within the design tolerance; the perigee was actually only 0.4 nautical miles short of the desired altitude. A 20 ft/sec overspeed condition at orbital insertion produced an increase of 11 nautical miles in the apogee.

Although the trajectory was designed for an orbital lifetime of several days, the Gemini I mission was considered complete after three orbital passes over Cape Kennedy. All primary and secondary mission objectives were achieved.

Adapter LA was procured by tne NASA as a spare adapter for this mission.

Gemini II Mission - The second Gemini mission was an unmanned suborbital flight launched at 9:04 a.m. EST, on 19 January 1965. The spacecraft was recovered by the primary recovery ship, the aircraft carrier, U.S.S. Lake Champlain, at 10:52 a.m., EST. Splashdown was within three miles of the target.

Spacecraft 2 contained production units of all equipment used on the later manned missions except the rendezvous radar and the drogue parachute systems. An automatic sequencing device was installed in the spacecraft to control the operation and the sequencing of the Gemini subsystems throughout the flight. Major spacecraft functions performed were spacecraft/launch vehicle separation, controlled 180 degree turnaround, adapter equipment jettison, retrofire, retrograde section jettison, controlled zero lift reentry

(10 degrees roll rate for 150 seconds), and parachute landing. The spacecraft was recovered 1848 nautical miles down range from the launch site. Flight-worthiness of the spacecraft and all major subsystems was adequately demonstrated.

Gemini III Mission - The third flight, the program's first manned mission, with command pilot Virgil I. Grisson and pilot John W. Young, was launched at 9:24 a.m. EST on 23 March 1965. The flight crew successfully completed the three-orbit mission, during which they employed several thruster firings to alter the spacecraft orbit and to perform small out-of-plane maneuvers.

The actual landing point was about 58 nautical miles short of the planned retrieval point. The angle-of-attack had been about 30 percent lower than predicted, which resulted in a lower lift to drag ratio and a corresponding reduction in the touchdown footprint. The flight data indicated a difference between the actual and the wind-tunnel-derived aerodynamics of the reentry vehicle. The entry experience acquired from this mission and the Gemini II flight were correlated with wind tunnel data to arrive at a more accurate prediction of the trim angle for later flights.

The mission was successfully concluded with recovery of the spacecraft by the prime recovery ship, the aircraft carrier U.S.S. Intrepid. Two of the principal benefits were the qualification it gave the world-wide tracking network and the experience it provided to operations personnel for longer missions.

Gemini IV Mission - The Gemini IV flight, scheduled for a four-day mission, was launched from Cape Kennedy at 10:16 a.m. EST, on 3 June 1965. The flight crew consisted of command pilot James A. McDivitt and pilot Edward H. White II. In preparation for longer missions, the objectives included: (1) evaluating the effects, on the two-man flight crew, of prolonged exposure to the space environment and (2) demonstrating extravehicular activity in space using the hand-held propulsion unit and the tether line.

The flight demonstrated the astronauts' ability to adjust perfectly to a weightless environment and to perform all mission tasks with efficiency; both astronauts were in excellent physical condition at the conclusion of the flight. Of 13 scheduled inflight experiments, the crew effectively conducted 11.

The mission was successfully concluded on 7 June 1965, after completing 62 revolutions and almost 98 hours in space. Recovery was made by the prime recovery ship, the aircraft carrier U.S.S. Wasp, at 2:28 p.m., EST. With minor changes, the Gemini spacecraft was considered flight-qualified for longer missions.

Gemini V Mission - Launched at 9:00 a.m. EST, 21 August 1965, this was the first long-duration flight to use fuel cells as the principal source of spacecraft power. Primary objectives included demonstrating an eight day flight capability and exposing command pilot L. Gordon Cooper, Jr. and pilot Charles Peter Conrad, Jr., to prolonged weightlessness in preparation for extended duration missions.

At the end of revolution 17, the spacecraft was powered up to a high load condition. A successful rendezvous radar test was conducted by tracking a transponder on the ground at Cape Kennedy. On the third day, a simulated Agena rendezvous was conducted, indicating that the spacecraft could have been placed within 0.3 nautical miles of an Agena target vehicle.

Spacecraft systems functioned normally during reentry, but ground entry transmission of incorrect navigational co-ordinates caused a landing 89 nautical miles short of the planned retrieval point. The spacecraft was recovered on 29 August 1965 by the aircraft carrier U.S.S. Lake Champlain, after making 120 revolutions and remaining in space for 190 hours. The experiment program was highly successful; 16 of the 17 planned experiments were conducted, and a large percentage of desired data was accumulated.

Gemini VI Mission - The flight of Gemini IV was the first rendezvous mission. This mission's primary objective was to achieve an orbital rendezvous with Spacecraft 7, which became the target vehicle after the Agena's failure to achieve orbit on 25 October 1965.

Spacecraft 6 was successfully launched at 8:37 a.m., EST, on 15 December 1965, with command pilot Walter M. Schirra, Jr. and pilot Thomas P. Stafford on board, 11 days after the launch of Spacecraft 7. A "closed loop" rendezvous was achieved about six hours after launch. Nine maneuvers were performed by Spacecraft 6 to effect rendezvous. Initial radar lock-on with

Gemini VII occurred at a range of 248 nautical miles, with continuous lock-on beginning at 235 nautical miles. After rendezvous, station keeping was performed for about three-and-a-half orbits, with the spacecraft as close as one foot apart. Walter M. Schirra, Jr., the command pilot of Spacecraft 6, performed an in-plane fly-around maneuver, maintaining a distance of 150 to 250 ft. from Spacecraft 7. Separation maneuvers were performed and the visibility of Spacecraft 7 as a target vehicle was evaluated. The flight progressed normally and was ended by a nominal entry and landing on 16 December within seven nautical miles of the planned retrieval point. All primary mission objectives were accomplished. The Gemini VI/VII mission established a record for the longest formation flight in space, a flight of 20 hours 22 minutes with the spacecraft within 62 miles of each other.

Gemini VII Mission - The Gemini VII mission, a maximum duration flight, was launched at 12:30 p.m., EST, on 4 December 1965. The flight crew consisted of command pilot Frank Borman and pilot James A. Lovell, Jr.. The primary objectives were to demonstrate a manned orbital flight of 14 days, and to evaluate the effects of the prolonged mission upon the crew. Secondary objectives included a rendezvous with Spacecraft 6, station keeping with that spacecraft and with the second stage of the launch vehicle, and the carrying out of 20 inflight experiments.

After insertion, the spacecraft performed station keeping with the launch vehicle, maintaining distances of between 60 and 150 ft for 15 minutes. A closer approach was not attempted because of the high tumbling rate of the launch vehicle. On the fifth day, the spacecraft was maneuvered into a favorable orbit for the rendezvous with Spacecraft 6. No further adjustments to this orbit were required.

The 14-day mission was successfully completed by landing the spacecraft within 6.4 nautical miles of the planned retrieval point on 18 December 1965. Recovery was made by the carrier U.S.S. Wasp. All primary and secondary mission objectives were accomplished. The flight also demonstrated that astronauts could endure long duration missions without harm.

Gemini VIII Mission - The eighth Gemini mission was the first rendezvous and docking mission with an Agena target vehicle. Spacecraft 8 was launched successfully at 11:41 a.m., EST, on 16 March 1966, following the launch of the Atlas-Agena target vehicle an hour and forty minutes earlier. Command pilot Neil A. Armstrong and pilot David R. Scott comprised the flight crew.

The primary objectives of rendezvous and docking were accomplished during the fourth spacecraft revolution. Secondary objectives of evaluating the auxiliary tape memory unit and demonstrating a controlled entry were also accomplished. Be use the mission was terminated early, extravehicular activity was not performed and only two of ten scheduled inflight experiments could be conducted.

The Agena target vehicle was inserted into a 161.3 nautical mile circular orbit by its primary propulsion system. Spacecraft 8 performed nine maneuvers to rendezvous with the target five hours and fifty-eight minutes after spacecraft lift-off. The spacecraft docked with the target vehicle after about 36 minutes of station keeping. Once docked, a 90-degree yaw maneuver was performed using the Agena attitude control system.

At 7:00 hours Ground Elapsed Time (GET), unexpected yaw and roll rates developed while the two vehicles were docked, but command pilot Armstrong was able to reduce these rates to essentially zero. However, after he had released the hand controller, the rates began to increase again and the crew found it difficult to control the spacecraft without using excessive amounts of propellant. The spacecraft was undocked and the yaw and roll rates then increased to about 300 degrees per second, causing the crew to deactivate the OAMS and to use both rings of the re-entry control system to reduce the rates. The problem was isolated to Number 8 OAMS thruster which fired continuously because its circuitry failed in an ON condition.

Because the re-entry control system had been activated, it was decided to terminate the mission during the seventh revolution in the secondary recovery area in the western Pacific Ocean. Retrofire was on time at 10:04 hours GET. The entry was nominal, resulting in a landing within seven nautical miles of the planned retrieval point. The crew and spacecraft were recovered by the U.S.S. Leonard Mason about three hours and eleven minutes after landing.

Gemini IX Mission - The ninth Gemini flight was a rendezvous and docking mission with the Augmented Target Docking Adapter (ATDA) used as the target vehicle after the Atlas failed to insert the Agena into orbit on 17 May 1966. The ATDA consisted of a Target Docking Adapter (TDA), a cylindrical equipment section, a re-entry control system for attitude stabilization, a battery module, and an ascent shroud.

The ATDA was successfully launched on 1 June 1966, into a nearly circular orbit of 161 nautical miles. The Gemini spacecraft was launched successfully at 8:39 a.m., EST, on 3 June 1966, with command pilot Thomas P. Stafford and pilot Eugene A. Cernan on board.

Rendezvous was accomplished by performing seven maneuvers during the spacecraft's third revolution. It was impossible to dock with the ATDA because the ascent shroud on the ATDA had not separated as planned. Inspection revealed that the quick-disconnect lanyards had not been properly attached. Two additional rendezvous were therefore performed according to the alternate plan. The first was an equi-period rendezvous (in which the spacecraft has the same orbital period as the target). The second was a rendezvous from above, which was to simulate conditions which could result if the Apollo command module was required to rendezvous with a disabled lunar module. A two hour Extra-Vehicular Activity (EVA) was accomplished, but fogging of the pilot's visor prevented evaluation of the astronaut maneuvering unit.

On the third day, several of the uncompleted inflight experiments were performed. A nominal entry in the primary recovery area resulted in a landing one-third mile from the planned retrieval point on 6 June 1966. Recovery was made by the aircraft carrier U.S.S. Wasp.

Gemini X Mission - The tenth Gemini flight marked the second successful rendezvous and docking mission with an Agena target vehicle. The Agena was launched on 18 July 1966 at 3:39 p.m., EST; Spacecraft 10 was launched about one hour and forty minutes later at the beginning of a 35-second launch window. The Agena was placed in a nearly circular orbit with an apogee of 162 nautical miles and a perigee of 156.6 nautical miles. A velocity increment of 26 ft/sec was subsequently applied to place Gemini X in a nearly perfect 145.1 by 86.3

nautical mile orbit.

Command pilot John W. Young and pilot Michael Collins completed the rendezvous maneuver during the fourth revolution as planned. Approximately 30 minutes later, the spacecraft docked with the Agena target vehicle. The spacecraft remained docked with the target vehicle for about 39 hours, during which a bending mode test was conducted to determine the dynamics of the docked configuration. In addition, a 49-minute standup EVA was performed, which included several photographic experiments. The Agena primary and secondary propulsion systems were used to perform six maneuvers in the docked configuration in preparation for a passive rendezvous with the Gemini VIII Agena target vehicle.

About three hours after separating from the Agena, the Gemini spacecraft achieved its second rendezvous. The Agena for Spacecraft 8 was in a stable attitude, allowing the flight crew to bring the spacecraft very close to the passive ATV. A 38-minute EVA was then performed. As part of this EVA, pilot Michael Collins retrived the micrometeorite package which had been stowed on the ATV.

The planned three-day mission was accomplished successfully and was followed by a nominal entry on 21 July 1966. Touchdown was within three nautical miles of the planned retrieval point.

Gemini XI Mission - Gemini XI was launched from Cape Kennedy on 12 September 1966 at 9:42 a.m., EST. The Agena target vehicle, with which it was to rendezvous and dock, had been launched one hour and thirty-seven minutes earlier. The primary objective was for command pilot Charles Conrad and Pilot Richard F. Gordon, Jr. to dock with the Agena during the first revolution.

Following spacecraft insertion, five maneuvers were performed by the crew to achieve the first-orbit rendezvous with the target vehicle. Docking with the Agena occurred at approximatley 1:34 GET. At 40:30 GET, using the Agena's primary propulsion system, the flight crew increased the apogee of the docked vehicles to 741.5 nautical miles. While at this altitude, sequences of photographic and scientific experiments were performed.

The spacecraft was undocked at 49:55 GET to begin the tether evaluation. The 100-foot tether line, which the pilot had attached to the docking bar on the previous day's EVA, was unreeled. A light tension was maintained on the tether and a slight pinning motion was imparted to create a small gravity field. Performance demonstrated that the rotation of two tethered vehicles was an economical and feasible method of achieving long-term, unattended station keeping. Approximately three hours after initiation of the maneuver, the crew fired the aft thrusters to remove the tension on the tether line. The docking bar was then pyrotechnically jettionsed, releasing the tether.

Re-entry was accomplished by using the automatic mode. Splashdown occurred at 8:59 a.m., EST, on 15 September 1966. The landing point was 2.5 miles from the prime recovery ship, the U.S.S. Guam.

Gemini XII Mission - Gemini XII was launched at 3:46 p.m., EST, on 11 November 1966. The spacecraft was inserted into an orbit with a 151.9 nautical mile apogee and a perigee of 86.9 nautical miles. As planned, rendezvous and docking were accomplished by command pilot James A. Lovell, Jr. and pilot Edwin Aldrin during the third revolution over the tracking ship U.S.S. Coastal Sentry, south of Japan.

By applying a retrograde burn of 43 ft/sec using the Agena's secondary propulsion system, the configuration was placed in a 154 nautical mile orbit. This permitted it to phase with the 12 November total solar eclipse over south America. A second eclipse-phasing maneuver was subsequently performed, enableing the crew to obtain the first solar eclipse photographs taken from space.

During the course of the mission, pilot Edwin Aldrin performed a total of five hours, 37 minutes of extravehicular activity, including the longest-duration single EVA to date (two hours, nine minutes). Pilot Aldrin also performed measured work tasks at the ATV and at a work station set up in the Gemini adapter section.

The gravity-gradient mode of the tethered vehicle exercise was successfully completed; the entire tethered exercise lasted four hours and seventeen minutes.

The spacecraft splashed down at 2:22 p.m., EST, on 15 November 1966, within 2.7 miles of the planned retrieval point. The further demonstrated the accuracy of the automatic entry mode.

The Gemini Program, concluded in November 1966 ahead of schedule and below anticipated costs, resulted in a record of 12 successful spacecraft flights and a total of 969 man hours in space. Major achievements were: demonstrating the ability to mate with another vehicle in space, demonstrating the greatly increased maneuverability and range by the combined spacecraft and target vehicle, discovering new techniques enabling man to perform work under "zero g" condition, and demonstrating a life support system which permitted man to survive for long periods in a space environment.

The Gemini flight record summary is shown in Table B-1.

Table B–1

GEMINI FLIGHT RECORD

MISSION	CREW (COMMAND PILOT FIRST)	LAUNCH	SPLASHDOWN	LENGTH	REMARKS
GEMINI 1		APRIL 8, 1964	APRIL 12, 1964		UNMANNED TEST OF SPACECRAFT LAUNCH VEHICLE INTEGRITY.
GEMINI 2		JANUARY 19, 1965	JANUARY 19, 1965		UNMANNED BALLISTIC TEST OF SPACECRAFT AND HEAT SHIELD.
GEMINI 3	VIRGIL I. GRISSOM JOHN W. YOUNG	9:24:00 A.M. EST, MARCH 23, 1965	2:17 P.M. EST, MARCH 23, 1965	3 REVOLUTIONS 4 HOURS, 53 MINUTES	FIRST U.S. TWO-MAN FLIGHT. FIRST SUCCESSFUL ORBIT CHANGING OF A MANNED SATELLITE.
GEMINI 4	JAMES A. MCDIVITT EDWARD M. WHITE, II	10:15:59 A.M. EST, JUNE 3, 1965	12:12:30 P.M. EST, JUNE 7, 1965	4 DAYS, 62 REVOLUTIONS 97 HOURS, 56 MINUTES, 31 SECONDS	FIRST U.S. EXTRAVEHICULAR ACTIVITY (EVA) BY PILOT WHITE, WHICH LASTED 20 MINUTES.
GEMINI 5	L. GORDON COOPER, JR. CHARLES PETER CONRAD, JR.	9:00:00 A.M. EST, AUGUST 21, 1965	7:56 A.M. EST, AUGUST 29, 1965	8 DAYS, 120 REVOLUTIONS 190 HOURS, 56 MINUTES	FIRST GEMINI USE OF FUEL CELLS. FIRST EIGHT-DAY MANNED FLIGHT.
GEMINI 7	FRANK BORMAN JAMES A. LOVELL, JR.	12:30:03 P.M. EST, DECEMBER 4, 1965	9:05:06 A.M. EST, DECEMBER 18, 1965	206 REVOLUTIONS 330 HOURS, 35 MINUTES, 17 SECONDS	FIRST U.S. TWO-WEEK MANNED SPACE FLIGHT.
GEMINI 6	WALTER M. SCHIRRA, JR. THOMAS P. STAFFORD	08:37:26 A.M. EST, DECEMBER 15, 1965	10:29:09 A.M. EST, DECEMBER 16, 1965	17 REVOLUTIONS 25 HOURS, 51 MINUTES, 43 SECONDS	WORLD'S FIRST SUCCESSFUL RENDEZVOUS OF TWO ORBITING SPACECRAFT AS IT CAME WITHIN 1 FT. OF GEMINI 7 AND STAYED WITHIN 62.13 MILES OF IT FOR 20 HOURS, 22 MINUTES.
GEMINI 8	NEIL A. ARMSTRONG DAVID R. SCOTT	11:41:02 A.M. EST, MARCH 16, 1966	10:23:08 P.M. EST, MARCH 16, 1966	7 REVOLUTIONS 10 HOURS, 42 MINUTES, 6 SECONDS	FIRST SUCCESSFUL DOCKING OF TWO SPACECRAFT IN ORBIT. MISSION ABORTED EARLY WHEN SPACECRAFT ATTITUDE CONTROL ROCKETS MALFUNCTIONED.
GEMINI 9	THOMAS P. STAFFORD EUGENE A. CERNAN	8:39:33 A.M. EST, JUNE 3, 1966	9:00:47 A.M. EST, JUNE 6, 1966	46 REVOLUTIONS 72 HOURS, 21 MINUTES, 14 SECONDS	PILOT CERNAN SPENT 2 HOURS, 9 MINUTES AND SET A NEW WORLD'S RECORD FOR AN ASTRONAUT ATTACHED TO SPACECRAFT BY ONLY A TETHER.
GEMINI 10	JOHN W. YOUNG MICHAEL COLLINS	5:20:26 P.M. EST, JULY 18, 1966	4:06:11 P.M. EST, JULY 21, 1966	44 REVOLUTIONS 70 HOURS, 46 MINUTES, 14 SECONDS	USED AGENA TO GO TO ALTITUDE OF 410 NAUTICAL MILES. FIRST DUAL RENDEZVOUS WITH AGENA 10 AND LATER WITH AGENA 8 TARGET VEHICLE. TWO EVA PERIODS.
GEMINI 11	CHARLES CONRAD RICHARD F. GORDON, JR.	9:42:26 A.M. EST, SEPTEMBER 12, 1966	8:59:34 A.M. EST, SEPTEMBER 15, 1966	45 REVOLUTIONS 71 HOURS, 17 MINUTES, 8 SECONDS	SET NEW MANNED SPACE FLIGHT RECORD OF 739.4 NAUTICAL MILES. ALSO, WORLD'S FIRST ONE-ORBIT RENDEZVOUS. TWO EVA PERIODS.
GEMINI 12	JAMES A. LOVELL, JR. EDWIN ALDRIN	3:46:00 P.M. EST, NOVEMBER 11, 1966	2:22 P.M. EST, NOVEMBER 15, 1966	59 REVOLUTIONS 94 HOURS, 36 MINUTES	THREE-ORBIT RENDEZVOUS TO SIMULATE LUNAR PROGRAM RENDEZVOUS. ALDRIN SET WORLD RECORD FOR TOTAL EVA DURING ONE MISSION WITH 5 HOURS, 37 MINUTES.

FIRST UNIT COST

ENTRY VEHICLE AVE PROCUREMENT	PRIME CONTRACTOR LABOR	MATERIAL, CFE, AND SUBCONTRACT
SUSTAINING ENGINEERING (E/V)	.64 (CESRE/KENGR)$^{.848}$ (KENGR) - .23 (CESSRE)	.10 (CSEE KENGR)(KMCS)
SUSTAINING TOOLING (E/V)	.16 (CPE KPROD) (KTOOL)	1.0 (CSTE KTOOL) (KMCS)
PRODUCTION, MATERIAL, CFE & SUBCONTRACT		
THERMAL/STRUCTURE		
STRUCTURE		
CREW SECTION	335 (WSCSP)$^{.766}$ (KMCSP) (KACSP) [1 - .05 (KMCSP)] (KPROD)	3950(WSCSP)$^{.766}$ (KMCSP)(KACSP)[.05 (KMCSP)] (KMCS)
CARGO PROPULSION SECTION	190 (WSCPP)$^{.766}$ (KMCPP) (KACPP) (KPS)[1-.05(KMCPP)] (KPROD)	2250 (WSCPP)$^{.766}$(KMCPP)(KACPP)(KPS)[.05(KMCPP] (KMCS)
AERODYNAMIC CONTROL SURFACES	325 (WSACSP)$^{.766}$(KMACSP)(1-.05(KMACSP))(KPROD)	3830(WSACSP)$^{.766}$(KMACSP)[.05(KMACSP)](KMCS)
THERMAL PROTECTION SYSTEM		
RADIATIVE	203(PSR)$^{-.322}$(SWTPR) (KPROD)	720 (KMTPR) (KSR)(PSR)$^{-.322}$(SWTPR)(KMCS)
ABLATIVE	203 (PSA)$^{-.322}$(SWTPA) (KPROD)	720 (KMTPA)(KSA)(PSA)$^{-.322}$ (SWTPA)(KMCS)
WATER COOLING	285 (WWC)$^{.766}$ (KPROD)	720 (WWC)$^{.766}$(KMCS)
LANDING GEAR	166 (WLG)$^{.766}$ (KPROD)	140 (WLG)$^{.766}$ (KMCS)
LAUNCH ESCAPE TOWER	75 (WSLET)$^{.766}$ (KPROD)	47 (WSLET)$^{.766}$ (KMCS)
INFLATABLE AERODYNAMIC DEVICES		
PARACHUTE	23 (WRPC)$^{.848}$ (KPROD)	1340 (WRPC)$^{.766}$ (KMCS)
SAILWING	23 (WRSW)$^{.848}$ (KPROD)	2010 (WRSW)$^{.766}$ (KMCS)
POWER SUPPLY AND ORDNANCE		
ELECTRICAL DISTRIBUTION	790 (WEPD)$^{.848}$ (KPROD)	530 (WEPD) (KMCS)
FUEL CELL	138 (WFC)$^{.848}$ (KPROD)	300000 (PKW)$^{.183}$ (NFC)$^{.848}$ (KMCS)
BATTERY	34 (WB)$^{.848}$(KPROD)	145 (BAT)$^{.422}$(NB)$^{.926}$(KMCS)
REACTANT SUPPLY SYSTEM	138 (WRSS)$^{.848}$ (KPROD)	107500 (EKWH)$^{.275}$ (KMCS)
HYDRAULICS & PNEUMATICS	285 (WHPN)$^{.766}$ (KPROD)	720 (WHPN)$^{.766}$ (KMCS)
ORDNANCE	188 (WORD)$^{.848}$ (KPROD)	1330 (WORD) (KMCS)
ECLS		
ECS — STORABLE GAS	130 (WECS)$^{.848}$ (KPROD)	487400(M)$^{.374}$(MT)$^{.127}$(KECSS)(KMCS)
ECS — CRYOGENIC GAS		548000(M)$^{.396}$(MT)$^{.203}$ (KECSC)(KMCS)
FURNISHINGS & EQUIPMENT	50 (WFE)$^{.848}$ (KPROD)	650 (WFE) (KMCS)
AVIONICS		
GUIDANCE & CONTROL	146 (WGC)$^{.848}$ (KPROD)	(AMGC) (KMCS)
TELECOMMUNICATIONS	160 (WTC)$^{.848}$ (KPROD)	(AMTC) (KMCS)
CREW STATION	386 (WCS)$^{.848}$ (KPROD)	5000 (WCS)$^{.766}$ (KMCS)
ON-BOARD CHECKOUT	146 (WOBC)$^{.848}$ (KPROD)	(AMOBC) (KMCS)
PROPULSION		
ENTRY ATTITUDE CONTROL	128 (WEAC)$^{.848}$ (KPROD)	
ENGINES		{[20,000 + 240 (FECRAD)$^{.700}$](NEECRA)$^{.926}$ + [35000 + 450 (FECABL)$^{.800}$](NEECAB)$^{.926}$} KMCS]
TANKS		46000 (VTEAC)$^{.310}$ (NTEAC)$^{.848}$ (KMCS)
LINES, VALVES, & MISC.		59000 (WECLVM)$^{.430}$ (KRED) (KMCS)
VERNIER MANEUVER SYSTEM	128 (WVM)$^{.848}$ (KPROD)	
ENGINES		[20000 + 240(FVORA)$^{.700}$] (NEVORA)$^{.926}$ + [35000 + 450(FVOAB)$^{.800}$] (NEVOAB)$^{.926}$ + [20000 + 240(FVDRA)$^{.700}$] (NEVDRA)$^{.926}$ + [35000 + 450(FVDAB)$^{.800}$] (NEVDAB)$^{.926}$ }(KMCS)
TANKS		[46000 (VTVMO)$^{.310}$ (NTVMO)$^{.848}$ + 46000 (VTVMD)$^{.310}$ (NTVMD)$^{.848}$] [KMCS]
LINES, VALVES, MISC.		59000 (WVMLVM)$^{.430}$ (KMCS)
MAIN ORBITAL MANEUVER	57 (WMOM)$^{.848}$ (KPROD)	
ENGINES		{[35000 + 450 (FMABL)$^{.800}$](NEMAB)$^{.926}$ + [350000 + 475(FMRGC)$^{.700}$] (NEMRGC)$^{.926}$ + [200000 + 113 (FMRGS)$^{.700}$] (NEMRGS)$^{.926}$}[KMCS]]
TANKS		[3000 (VMOOX)$^{.623}$ (KPRMO) (NTMOO)$^{.848}$ + 3000 (VMDOX)$^{.623}$ (KPRMO) (NTMDO)$^{.848}$ + 3000 (VMOF)$^{.623}$ (KPRMF) (NTMOF)$^{.848}$ + 3000 (VMDF)$^{.623}$ (KPRMF) (NTMDF)$^{.848}$]KMCS]
LINES, VALVES, MISC.		59000 (WMLVM)$^{.430}$ (KMCS)

ENTRY VEHICLE AVE PROCUREMENT	PRIME CONTRACTOR LABOR	MATERIAL, CFE, AND SUBCONTRACT
LAUNCH UPPER STAGE		
ENGINES	30 (WLUSE)$^{.848}$ (KPROD)	{(KPRLC) [350000 + 475 (FLRGC)$^{.700}$](NELRGC)$^{.926}$ + [270000 + 24 (FLRGS $^{.800}$](NELRGS)$^{.926}$ }[KMCS]
TANKS (INTERNAL)	[160 (WLINTS)$^{.766}$ + 160 (WLINTT)$^{.766}$] KPROD][KPT]	[99 (WLINTS)$^{.766}$ + 99 (WLINTT) $^{.766}$] [KMCS] [KPT]
TANKS (EXTERNAL)	160 (WLEXT)$^{.766}$ (NTEXT) $^{.848}$ (KPROD) (KPT)	99 (WLEXT)$^{.766}$ (NTEXT)$^{.848}$ (KMCS) (KPT)
LINES, VALVES, MISC.		5100 (WLLVM)$^{.430}$ (KMCS)
LAUNCH ESCAPE SOLID ROCKET MOTORS	118 (WLESE)$^{.848}$ (KPROD)	[652 (ITLEL)$^{.328}$ (NMLEL)$^{.926}$ + 652 (ITLEH)$^{.328}$ (NMLEH)$^{.926}$] [KMCS]
DEORBIT SOLID ROCKET MOTORS	118 (WDO) $^{.848}$ (KPROD)	652 (ITDO) $^{.328}$ (NMDO)$^{.926}$ (KMCS)
LANDING ASSIST SOLID ROCKET MOTORS	118 (WLA) $^{.848}$ (KPROD)	652 (ITLA) $^{.328}$ (NMLA) $^{.926}$ (KMCS)
FINAL ASSEMBLY & CHECKOUT	.06 (CPSE) + .96 (CPSYSE)	.40 (CPFC KPROD) (KMCS)
MISSION MODULE AVE PROCUREMENT		
SUSTAINING ENGINEERING (M/M)	.64 (CESRM KENGR)$^{.848}$ (KENGR) + .23 (CESSRM)	.10 (CSEM KENGR) (KMCS)
SUSTAINING TOOLING (M/M)	.16 (CPM KPROD) (KTOOL)	1.0 (CSTM/KTOOL) (KMCS)
PRODUCTION, MATERIAL, CFE, & SUBC.		
STRUCTURE		
SIMPLE ADAPTER	113 (WSA)$^{.766}$ (KMAP) [1-.05 (KMAP)] (KPROD)	1330 (WSA)$^{.766}$ (KMAP)(.05 KMAP)(KMCS)
CARGO PROPULSION SECTION	190 (WSCPM)$^{.766}$ (KMCPMP) (KACPMP) [1-.05 (KMCPMP)] (KPROD)	2250 (WSCPM)$^{.766}$ (KMCPMP)(KACPMP)(.05 KMCPMP)(KMCS)
POWER SUPPLY & ORDNANCE		
ELECTRICAL DISTRIBUTION	482 (WEPDM)$^{.848}$ (KPROD)	530 (WEPDM) (KMCS)
FUEL CELL	76 (WFCM) $^{.848}$ (KPROD)	300000 (PKWM) $^{.183}$ (NFCM)$^{.848}$ (KMCS)
BATTERY	19 (WBM) $^{.848}$ (KPROD)	145 (BATM)$^{.422}$ (NBM)$^{.926}$ (KMCS)
REACTANT SUPPLY SYSTEM	76 (WRSSM) $^{.848}$ (KPROD)	107500 (EKWHM)$^{.275}$ (KMCS)
ORDNANCE	131 (WORDM)$^{.848}$ (KPROD)	1330 (WORDM) (KMCS)
ECLS		
ECS STORABLE GAS	{76 (WECSM)$^{.848}$ (KPROD)	487400(M)$^{.374}$ (MT)$^{.127}$ (KECSSM) (KMCS)
ECS CRYOGENIC GAS		548000(M)$^{.396}$ (MT)$^{.203}$ (KECSCM)(KMCS)
AVIONICS		
GUIDANCE & CONTROL	80 (WGCM)$^{.848}$ (KPROD)	AMGCM (KMCS)
TELECOMMUNICATIONS	108 (WTCM)$^{.848}$ (KPROD)	AMTCM (KMCS)
CREW STATION	212 (WCSM) $^{.848}$ (KPROD)	5000 (WCSM) $^{.766}$ (KMCS)
ON-BOARD CHECKOUT	80 (WOBCM)$^{.848}$ (KPROD)	AMOBCM (KMCS)
PROPULSION		
VERNIER MANEUVER SYSTEM	76 (WVMM)$^{.848}$ (KPROD)	
ENGINES		{[20000 + 240 (FVORAM)$^{.700}$] (NEVORM)$^{.926}$ + [35000 + 450 (FVOABM)$^{.800}$] (NEVOAM)$^{.926}$ +[20000 + 240 (FVDRAM)$^{.700}$] (NEVDRM)$^{.926}$ + [35000 + 450 (FVDABM)$^{.800}$] (NEVDAM)$^{.926}$}[KMCS]
TANKS		[46000 (VTVMOM)$^{.310}$ (NTVMOM)$^{.848}$ + 46000 (VTVMDM)$^{.310}$ (NTVMDM)$^{.848}$] (KMCS)
LINES, VALVES & MISC		59000 (WVLVMM)$^{.430}$ (KMCS)
MAIN ORBITAL MANEUVER	57 (WMOMM)$^{.848}$ (KPROD)	
ENGINES		{[35000 + 450 (FMABLM)$^{.800}$] (NEMABM)$^{.926}$ + [350000 + 475 (FMRGCM)$^{.700}$](NEMRCM)$^{.926}$ + [200000 + 113 (FMRGSM)$^{.700}$](NEMRSM) $^{.926}$}[KMCS]
TANKS		[3000 (VMOOXM)$^{.623}$ (KPRMOM) (NTMOOM)$^{.848}$ + 3000 (VMDOXM)$^{.623}$ (KPRMOM) (NTMDOM)$^{.848}$ + 3000 (VMOFM) $^{.623}$ (KPRMFM) (NTMOFM) $^{.848}$ + 3000 (VMDFM)$^{.623}$ (KPRMFM) (NTMDFM) $^{.848}$] [KMCS]
LINES, VALVES & MISC		59000 (WMLVMM)$^{.430}$ (KMCS)
DEORBIT SOLID ROCKET MOTORS	65 (WDOM)$^{.848}$ (KPROD)	652 (ITDOM)$^{.328}$ (NMDOM)$^{.926}$ (KMCS)
LAUNCH ESCAPE SOLID ROCKET MOTORS	65 (WLESEM)$^{.848}$ (KPROD)	652 (ITLELM)$^{.328}$ (NMLELM)$^{.926}$ (KMCS)
FINAL ASSEMBLY & CHECKOUT	.06 (CPSM) + .96 (CPSYSM)	.40 (CPFCM KPROD) (KMCS)

RESEARCH, DEVELOPMENT, TEST AND EVALUATION PHASE

	ENGINEERING LABOR	TOOLING LABOR	MATERIAL, CFE, & SUBCONTRACT
SPACECRAFT (S/C)			
S/C PROJECT MANAGEMENT & ADMINISTRATION	.06 (CRE)		1.00 (.06 CRE/KENGR)(KMCS)
ENTRY VEHICLE DESIGN & DEVELOPMENT			
THERMAL STRUCTURE			
CREW SECTION (TOOLING)		880$(WSCSET)^{.766}$ (KACST)(KCT)(KTOOL)	1.0 (CTRCSE/KTOOL)(KMCS)
CREW SECTION (DESIGN)	3510 $(WSCSET)^{.485}$(KACSE) (KCCS)(KDCS)(KENGR)		
CREWSECTION (TEST)	1040 $(WSCSET)^{.766}$ (KENGR)		
CARGO/PROPULSION SECTION (TOOLING)		700$(WSCPET)^{.766}$ (KACPT)(KCT)(KTOOL)	1.0 (CTRCPE/KTOOL)(KMCS)
CARGO/PROPULSION SECTION (DESIGN)	3510 $(WSCPET)^{.485}$(KACPE)(KCCP)(KDCP)(KENGR)		
CARGO/PROPULSION SECTION (TEST)	830$(WSCPET)^{.766}$(KENGR)		
THERMAL PROTECTION – ABLATIVE	15750 $(SWTPA)^{.485}$ $(PSA)^{-.234}$(KENGR)	3800 $(SWTPA)^{.766}$ $(PSA)^{-.234}$ (KSA)(KTOOL)	1.0 (CTRTPE/KTOOL)(KMCS)
LANDING GEAR	440 $(WLG)^{.766}$ (KENGR)	230 $(WLG)^{.766}$ (KTOOL)	1.0 (CTRLG/KTOOL)(KMCS)
LAUNCH ESCAPE TOWER (TOOLING)		130 $(WSLET)^{.766}$ (KTOOL)	1.0 (CTRLT/KTOOL)(KMCS)
LAUNCH ESCAPE TOWER (DESIGN)	535 $(WSLET)^{.485}$(KENGR)		
LAUNCH ESCAPE TOWER (TEST)	130 $(WSLET)^{.766}$ (KENCR)		
INFLATABLE AERODYNAMIC DEVICES			
PARACHUTE	42 $(CMPCE/KMCS)^{.485}$(KENGR)		14330 $(WCDPC)^{.766}$(KMCS)
SAILWING	42 $(CMSWE/KMCS)^{.485}$(KENGR)		21500 $(WCDSW)^{.766}$ (KMCS)
POWER SUPPLY & ORDNANCE			
ELECTRICAL DISTRIBUTION	3540 $(WEPD)^{.766}$(KENGR)		2380 (WEPD)(KMCS)
FUEL CELL	17 $(CMFCE/KMCS)^{.485}$(KENGR)		3800000$(PKW)^{.379}$$(NFC)^{.263}$(KMCS)
BATTERY	320$(WB)^{.485}$(KENGR)		44000$(BAT)^{.120}$(KMCS)
REACTANT SUPPLY SYSTEM	17$(CMRSSE/KMCS)^{.485}$ (KENGR)		1260000 $(EKWH)^{.275}$ (KMCS)
HYDRAULICS & PNEUMATICS	1600 $(WHPN)^{.766}$(KENGR)	320 $(WHPN)^{.766}$ (KTOOL)	7650$(WHPN)^{.766}$ (KMCS)
ORDNANCE	2950$(WORD)^{.766}$(KENGR)		33670(WORD)(KMCS)
ECLS			
ECS	77$(CMECSE/KMCS)^{.485}$ (KENGR)		6154000$(M)^{.485}$ $(MT)^{.263}$ (KMCS)(.8 KECSS + KECSC)
FURNISHINGS & EQUIPMENT	3700$(WFE)^{.485}$ (KENGR)		300000$(WFE)^{.263}$(KMCS)
AVIONICS			
GUIDANCE & CONTROL	52 $(CMGCE/KMCS)^{.485}$ (KENCR)		(BMGC)(KMCS)
TELECOMMUNICATIONS	$[62(CMTCE/KMCS)^{.485} + 3160\ (WDEV)^{.485}]$(KENGR)		(BMTC)(KMCS)
CREW STATION	2430 $(WCS)^{.766}$ (KENGR)		35300 $(WCS)^{.766}$ (KMCS)
ONBOARD CHECKOUT	52 $(CMOBCE/KMCS)^{.485}$ (KENGR)		(BMOBC)(KMCS)
PROPULSION			
ENTRY ATTITUDE CONTROL SYSTEM	21 $(CMEACE/KMCS)^{.485}$ (KENGR)		
ENGINES			$\{[LREECR][5000000 + 48600\ (FECRAD)^{.678}] + [LREECA][10000000 + 84000\ (FECABL)^{.678}]\}$ (KMCS)
TANKS			1750000 $(VTEAC)^{.13}$ (KMCS)
LINES, VALVES, MISC			1265000 $(WEAC)^{.410}$ (KMCS)

RESEARCH, DEVELOPMENT, TEST AND EVALUATION PHASE (Continued)

	ENGINEERING LABOR	TOOLING LABOR	MATERIAL, CFE, & SUBCONTRACT
VERNIER MANEUVER SYSTEM	21 (CMVME KMCS)$^{.485}$ (KENGR)		
ENGINES			{(LREVOR)[(5000000 + 48600 (FVORA)$^{.678}$] + (LREVOA)[10000000 + 84000 (FVOAB)$^{.678}$] + (LREVDR) [5000000 + 48600 (FVDRA)$^{.678}$] + (LREVDA)[10000000 + 84000 (FVDAB)$^{.678}$]} {KMCS}
TANKS			1750000 [(VTVMO)$^{.13}$ + (VTVMD)$^{.13}$] [KMCS]
LINES, VALVES, MISC			1265000 (WVM)$^{.410}$ (KMCS)
MAIN ORBITAL MANEUVER SYSTEM	21 (CMMOME KMCS)$^{.485}$ (KENGR)		
ENGINES			{(LREMA)[10000000 + 84000 (FMABL)$^{.678}$ + (LREMC)[50000000 + 1405000 (FMRGC)$^{.422}$ + (LREMS) [50000000 + 865000 (FMRGS)$^{.422}$]} KMCS}
TANKS			96000 [(VMOOX)$^{.600}$ + (VMDOX)$^{.600}$ + (VMDF)$^{.600}$ + (VMOF)$^{.600}$] [KMCS]
LINES, VALVES, & MISC			1265000 (WMOM)$^{.410}$ (KMCS)
LAUNCH UPPER STAGE			
ENGINES	11600 (WLUSE)$^{.570}$ (KENGR)		{[50000000 + 1405000 (FLRGC)$^{.422}$](PCLRGC)(KPRLUC) + [50000000 + 865000 (FLRGS)$^{.422}$] (PCLRGS) + KPRL (FLRGC + FLRGS)} { KMCS}
TANKS (INTERNAL), TOOLING		[610(WLINTS)$^{.766}$ + (WLINTT)$^{.766}$] [KTOOL]	1.0(CTRTI KTOOL)(KMCS)
DESIGN	[2440][(WLINTS)$^{.485}$ + (WLINTT)$^{.485}$] [KENGR]		
TEST	[531][(WLINTS)$^{.766}$ + (WLINTT)$^{.766}$] [KENGR]		
TANKS (EXTERNAL), TOOLING		610(WLEXT)$^{.766}$ (KTOOL)	1.0 (CTRTE KTOOL)(KMCS)
DESIGN	2440 (WLEXT)$^{.485}$ (KENGR)		
TEST	531 (WLEXT)$^{.766}$ (KENGR)		
LINES, VALVES, & MISC			.50 (CELUSE KENGR) (KMCS)
LAUNCH ESCAPE SOLID ROCKET MOTOR	17(CMLESE KMCS)$^{.485}$ (KENGR)		[390000 (ITLEL)$^{.193}$ + 390000 (ITLEH)$^{.193}$] [KMCS]
DEORBIT SOLID ROCKET MOTOR	17 (CMDSRE KMCS)$^{.485}$ (KENGR)		390000 (ITDO)$^{.193}$ (KMCS)
LANDING ASSIST SOLID ROCKET MOTOR	17 (CMLAE KMCS)$^{.485}$ (KENGR)		390000 (ITLA)$^{.193}$ (KMCS)
MISSION MODULE DESIGN & DEVELOPMENT			
STRUCTURE			
SIMPLE ADAPTER (TOOLING)		186(WSA)$^{.766}$ (KTOOL)	1.0 (CTRA KTOOL)(KMCS)
SIMPLE ADAPTER (DESIGN)	760 (WSA)$^{.485}$ (KENGR)		
SIMPLE ADAPTER (TEST)	187 (WSA)$^{.766}$ (KENGR)		
CARGO PROPULSION SECTION (TOOLING)		480(WSCPM)$^{.766}$ (KACPMT)(KTOOL)	1.0 (CTRCPM KTOOL)(KMCS)
CARGO PROPULSION SECTION (DESIGN)	3050(WSCPM)$^{.485}$ (KACPME)(KDCPM)(KENGR)		
CARGO PROPULSION SECTION (TEST)	664 (WSCPM)$^{.766}$ (KENGR)		

RESEARCH, DEVELOPMENT, TEST AND EVALUATION PHASE (Continued)

	ENGINEERING LABOR	TOOLING LABOR	MATERIAL, CFE, & SUBCONTRACT
POWER SUPPLY & ORDNANCE			
ELECTRICAL DISTRIBUTION	1850 (WEPDM)$^{.766}$ (KENGR)		2380 (WEPDM)(KMCS)
FUEL CELL	17 (CMFCM/KMCS)$^{.485}$ (KENGR)		3800000 (PKWM)$^{.379}$ (NFCM)$^{.263}$(KMCS)
BATTERIES	320 (WBM)$^{.485}$ (KENGR)		44000 (BATM)$^{.120}$(KMCS)
REACTANT SUPPLY SYSTEM	17 (CMRSSM/KMCS)$^{.485}$ (KENGR)		1260000 (EKWHM)$^{.275}$ (KMCS)
ORDNANCE	1740 (WORDM)$^{.766}$ (KENGR)		33670 (WORDM)(KMCS)
ECLS			
ECS	52 (CMECSM/KMCS)$^{.485}$ (KENGR)		6154000 (M)$^{.485}$ (MT)$^{.263}$ (KMCS) (.8 KECSSM + KECSCM)
AVIONICS			
GUIDANCE & CONTROL	52 (CMGCM/KMCS)$^{.485}$ (KENGR)		BMGCM (KMCS)
TELECOMMUNICATIONS	[62(CMTCM/KMCS)$^{.485}$ + 1140 (WDMM)$^{.485}$] (KENGR)		BMTCM (KMCS)
CREW STATION	1340 (WCSM)$^{.766}$ (KENGR)		35300 (WCSM)$^{.766}$ (KMCS)
ON-BOARD CHECKOUT	52 (CMOBCM/KMCS)$^{.485}$ (KENGR)		BMOBCM (KMCS)
PROPULSION			
VERNIER MANEUVER SYSTEM	21 (CMVMM/KMCS)$^{.485}$ (KENGR)		
ENGINES			{(LEVORM) [5000000 + 48600 (FVORAM)$^{.678}$] + (LEVOAM) [10000000 + 84000 (FVOABM)$^{.678}$] + (LEVDRM) [5000000 + 48600 (FVDRAM)$^{.678}$] + (LEVDAM) [10000000 + 84000 (FVDABM)$^{.678}$]} {KMCS}
TANKS			1750000 [(VTVMOM)$^{.13}$ + (VTVMOM$^{.13}$)] [KMCS]
LINES, VALVES, MISC			1265000 (WVMM)$^{.410}$ (KMCS)
MAIN ORBITAL MANEUVER	21 (CMMOMM/KMCS)$^{.485}$ (KENGR)		
ENGINES			{(LREMAM) [10000000 + 84000 (FMABLM)$^{.678}$ + (LREMCM) [50000000 + 1405000 (FMRGCM)$^{.422}$] + (LREMSM) [50000000 + 865000 (FMRGSM)$^{.422}$]} {KMCS}
TANKS			96000 [(VMOOXM)$^{.600}$ + (VMDOXM)$^{.600}$ + (VMOFM)$^{.600}$ + (VMDFM)$^{.600}$] [KMCS]
LINES, VALVES, MISC			1265000 (WMOMM)$^{.410}$(KMCS)
DEORBIT SOLID ROCKET MOTORS	17 (CMDSRM KMCS)$^{.485}$ (KENGR)		390000 (ITDOM)$^{.193}$ (KMCS)
LAUNCH ESCAPE SOLID ROCKETMOTORS	17 (CMLESM KMCS)$^{.485}$ (KENGR)		390000 (ITLELM)$^{.193}$ (KMCS)

RESEARCH, DEVELOPMENT, TEST AND EVALUATION PHASE (Continued)

	ENGINEERING LABOR	PRODUCTION LABOR	MATERIAL, CFE & SUBCONTRACT
AGE			
NONRECURRING			
HANDLING & SUPPORT	.07 (CESRE + CESRM)		
SUBSYSTEMS CHECKOUT	.35(CESSRE + CESSRM)		
RECURRING			.10 (CMRSYS)
HANDLING & SUPPORT	.05[.07 (CESRE + CESRM)] (QAGE 1)	.05(CPSE + CPSM)(QAGEI)	.22(CMTSTR)(QAGEI)
SUBSYSTEMS CHECKOUT	.05[.35(CESSRE + CESSRM)] (QAGE 1)	.88(CPSYSE + CPSYSM)(QAGEI)	.80 (CMTSYS)(QAGEI)
FACILITIES			
RECOVERY SITE FACILITIES	}[LLM][16.468 (1−E2S) + 2.065 (E2S)(NS) −1.33 (VLM)(1−E2S) + .205 (E2S)(NS)] + [11.54 (1−LLM)]} }3125 (KLRS)}		304(CPRFRS)(KMCS (KLRS)]
LAUNCH SITE FACILITY ACTIVATION	220102 (KLRS)		
LAUNCH SITE CONSTRUCTION			4.0 (CPRFLA)(KMCS KLRS) (3376) $(TSC)^{.485}$(KMCS)
TRAINERS	.4 (CSEE + CSEM)	.20(CTP)	1.60 (CMTSTR + CMTSYS)
SYSTEM INTEGRATION			
SYSTEM ENGINEERING	.50 (CEDD)		.05[(.50 CEDD)/ENGR)(KMCS)]
SYSTEM TEST OPERATIONS			
AIRDROP TEST OPERATIONS	[536,400 (KLRS) + 13340000 (KMCS)] (LSTOA)		.623 (CAHTS) (KMCS) (LSTOA)
GROUND TEST OPERATIONS			
WIND TUNNEL	95000(KCWT)(KENGR)		
THERMAL QUALIFICATION	1580 $(WDEV + WDMM)^{.600}$ (KENGR)		
STATIC FIRE (L.U.S.)	[267600 + 49500 (QFI−1)] $(NE)^{.26}$ $(FLRGS + FLRGC)^{.14}$ (KLRS)		[.75 (CRSSF/KLRS) + KPRL2(QF)(WPLUS) + KPRL1 (FLRGS + FLRGC)(NE)][KMCS]
BOOSTED FLIGHT TEST OPERATIONS			
LAUNCH OPERATIONS	(KLRS)[$\sum_{N-1}^{QF2}$ 18590 $(N)^{-.400}$ + 10094 $(N)^{-.349}$ + 19373 $(N)^{-.025}$ + 12160 $(N)^{-.197}$ + 13831 $(N)^{-.238}$ + 45325 $(N)^{-1.006}$] [(2.11 × 10^{-4}) $(TSC)^{.485}$] $\frac{52.13 \times 10^5}{14-4(BAL)}$(USP)]{		[.1182 (WLOH) + 1.2825 (WLFH) + .8395 (WFOC) + .2310 (WSTO)] (QF2) (KMCS)
LAUNCH AREA SUPPORT COST	}($\sum_{N-1}^{QF2}$ 76301 $(N)^{-.314}$)(2.11 × 10^{-4}) $(TSC)^{.485}$ + 30 281[36 (MBV) + 55 (IBV) + 44 (MLB) + 64 (ILB)]}} KLRS}		(1.6)(KMCS)[(STOFP2)'(KLRS)]
MISSION CONTROL SUPPORT	}6942[36 (MBV) + 55 (IBV) + 44 (MLB) + 64 (ILB)]}(KLRS)		
AGE MAINTENANCE	($\sum_{N\ 1}^{QF2}$ 162251 $(N)^{-.933}$)(KLRS)		.10 (CRAGR)
FACIL. MAINTENANCE	($\sum_{N\ 1}^{QF2}$ 38218 $(N)^{-.831}$)(2.11×10^{-4}) $(TSC)^{.485}$ (KLRS)		.01 (CRFAC)

RESEARCH, DEVELOPMENT, TEST AND EVALUATION PHASE (Continued)

	ENGINEERING LABOR	PRODUCTION LABOR	MATERIAL, CFE, & SUBCONTRACT
RECOVERY OPER COST CUSTOMER COST	][(1-VLM)(168000(1-E2S) · 84000 (E2S)(NS)) · (VLM)(LLM)(24000 (1-E2S) · 120000 (E2S)(NS)) · 200000 · (VLM) 42000 · 528000 (1-LLM)][QF2] · [(1- VLM)(46166 (1-E2S) · 21500 (E2S) (NS) · (VLM)(LLM)(42500 (1-E2S) · 19333 (E2S) (NS)) · 115500 (1-LLM)][36 (MBV) · 55 (IBV) · 44 (MLB) · 64 (ILB)] [] KECON [		
LAUNCH SITE PECULIAR AGE	(814052) (KLRS)		2.4 (CRPLSA)(KMCS/KLRS)
TRANSPORTATION			(KMCS)(QF2)[20000 (ATS) · 14000 (LTS) · 115000 (BTS)]
MOCKUPS	565 (WDEV · WDMM)$^{.485}$ (KENGR)	.20 (CTP)	1.0(.20 CTP/KPROD) (KMCS)
SYSTEM TEST HARDWARE			
AIRDROP TEST HARDWARE			
SUSTAINING ENGINEERING	(.33) (CSEE) (QA1)		(.10) (CASE/KENGR) (KMCS)
SUSTAINING TOOLING		(.10) (CAHP/KPROD) (KTOOL)	1.0 (CAST/KTOOL) (KMCS)
PRODUCTION, MATL, CFE & SUBC			
THERMAL/STRUCTURE			
STRUCTURE		.7 (QA1) (CPSCS/KMCSP + 1.2 CPSAC/KMACSP)	.7 (QA1) (CMSCS/KMCSP + 1.2 CMSAC/KMACSP)
THERMAL PROTECTION		.54 (QA1) (CPTPR + CPTPA)	.84 (QA1) (CMTPR/KMTPR + CMTPA/KMTPA)
LANDING GEAR		(.77)(CPLG) (QA1)	(.85) (CMLG) (QA1)
INFLATABLE AERO DEV			
PARACHUTE		(.77) (CPP) (QA1)	(.85) (CMP) (QA1)
SAILWING		(.77) (CPSW) (QA1)	.85 (CMSW))QA1)
POWER SUPPLY & ORDNANCE			
ELECTRICAL DISTRIBUTION		60000 (KPROD) (QA1)	100000 (KMCS) (QA1)
BATTERIES		1200 (KPROD) (QA1)	3200 (KMCS) (QA1)
HYDRAULICS & PNEUMATICS		(.77) (CPHP) (QA1)	.85 (CMHP)(QA1)
ORDNANCE		(.10) (CPO) (QA1)	(.10) (CMO) (QA1)
ECLS			
ECS		6000 (KPROD) (QA1)	180000 (KMCS) (QA1)
FURNISHINGS & EQUIPMENT		2500 (KPROD) (QA1)	50000 (KMCS) (QA1)
AVIONICS			
GUIDANCE & CONTROL		17000 (KPROD) (QA1)	1320000 (KMCS) (QA1)
TELECOMMUNICATIONS		17000 (KPROD) (QA1)	1500000 (KMCS) (QA1)
CREW STATION		.77 (CPCS) (QA1)	.85 (CMCS) (QA1)
PROPULSION			
LANDING ASSIST		(.77) (CPLA) (QA1)	.92 (CMLA) (QA1)
FINAL ASSEMBLY & CHECKOUT		(.06) (CAPTS) + .50 (CAPSS)	.40 (CAHFC/KPROD) (KMCS)
GROUND TEST HARDWARE TYPICAL EQUATION		(FIRST UNIT SUBSYSTEM COST) (QGI)	(FIRST UNIT SUBSYSTEM COST) (QGI)
BOOSTED FLIGHT TEST (TYPICAL EQUATION)		(FIRST UNIT SUBSYSTEM COST)(QUANTITY)^{XLC}	(FIRST UNIT SUBSYSTEM COST)(QUANTITY)^{XLC}
AVE PROCUREMENT SPARES		.20 (AVE PROCUREMENT)	.20 (AVE PROCUREMENT)
INVESTMENT PHASE			
INVESTMENT PHASE - TYPICAL EQUATIONS			
AVE PROCUREMENT	(FIRST UNIT COST) (QF)^{XLC}	(FIRST UNIT SUBSYSTEM COST)(QF)^{XLC}	(FIRST UNIT SUBSYSTEM COST)(QF)^{XLC}
SPARES		.10 (AVE PROCUREMENT)	.10 (AVE PROCUREMENT)
ADDITIONAL AGE			
HANDLING & SUPPORT	.05[.07(CESRE · CESEM)]QAGE 2	.05[CPSE · CPSM) (QAGE2)	.22 (CMTSTR) (QAGE 2)
SUBSYSTEMS CHECKOUT	.05[.35(CESSRE + CESSRM)]QAGE 2	.88(CPSYSE + CPSYSM) (QAGE 2)	.80(CMTSYS) (QAGE 2)
ADDITIONAL FACILITIES			250000000 (KMCS)

OPERATIONAL PHASE

	PRIME CONTRACTOR LABOR/CUSTOMER COST	MATERIAL, CFE & SUBCONTRACT
OPERATIONAL PHASE		
SPACECRAFT		
LAUNCH OPERATIONS	$\{[\sum_{N=QF2}^{10} [18590(N)^{-.400} + 10094(N)^{-.349} + 19373(N)^{-.025}$	$[.1182(WLOH) + 1.2825(WLFH)$
	$+ 12160(N)^{-.197} + 13813(N)^{-.238} + 45325(N)^{-1.006}$	$+ .8395(WFOC) + 2.231(WSTO)]$
	$+ \sum_{N=11}^{QI2} [8390 + (35874/N) + 19373(N)^{-.025}$	$(QI2 - QF2)(KMCS)$
	$+ [10000/(1.4587 - (1.62251/N))] + [10000/(1.44312$	
	$-(1.845/N))] + [10000/3.6778-(13.3646/N)]$	
	$\}(2.11\times10^{-4})(TSC)^{.485}\}+\{1.74\times10^{5}(\frac{QI2-QF2}{PL})^{-.583}\quad(QI2-QF2)(USP)\}](KLRS)$	
LAUNCH AREA SUPPORT	$[(\sum_{N=QF2}^{QI2} 76301(N)^{-.314})(2.11\times10^{-4}(TSC)^{.485})$	$1.6(COPLAS)(KMCS)/(KLRS)$
	$+ 30281(12\,PL + 11)]\,[KLRS]$	
MISSION CONTROL SUPPORT	$6942(12\,PL + 11)(KLRS)$	
AGE MAINTENANCE	$(\sum_{N=QF2}^{QI2} 162251(N)^{-.933})(KLRS)$	$1.6\,PL(COPAM)(KMCS)/(KLRS)$
FACILITY MAINTENANCE	$(\sum_{N=QF2}^{QI2} 38218(N)^{-.831})(2.11\times10^{-4})(TSC)^{.485}(KLRS)$	$.16\,PL(COPFM)(KMCS)(KLRS)$
RECOVERY OPERATIONS CUSTOMER COST	$[[(1 - VLM)(168000(1-E2S) + 84000(E2S)(NS)) + (VLM)(LLM)(240000(1 - E2S)$	
	$+ 120000(E2S)(NS)) + 200000 + 42000(VLM) + 528000(1 - LLM)](QI2 - QF2)$	
	$+[(1 - VLM)(46166(1 - E2S) + 21500(E2S)(NS)) + (VLM)(LLM)(42500(1-E2S)$	
	$+ 19333(E2S)(NS)) + 115500(1 - LLM)](12\,PL + 3)](KECON)$	
RECERTIFICATION	$1.4\{[31.2(SWTPA) + 19.2(SWTPR)][2.11\times10^{-4}][TSC]^{.485}$	$(\sum_{N=1}^{NR}(N)^{-.152}]\{.165(CMSSE)$
	$[\sum_{N=1}^{NR\leq100}(N)^{-.415} + \sum_{N=101}^{NR}(N)^{-.234}]$	$+ .22(CMSGE + CPSGE)]\,[KMCS]$
	$+[15528(BAL) + 16299(1 - BAL) + 3600(NE)]\quad[\sum_{N=1}^{NR}(N)^{-.234}]$	
	$+[(1-.8TDS)][AGEF][21060 + 1375(NE) + 12000(HFT)]$	
	$[\sum_{N=1}^{NR}(N)^{-.152}]\}\{KPROD\}$	
TRANSPORTATION		$\{(N)[20000(ATS) + 14000(LTS)$
		$+ 115000(BTS)] + (NR)$
		$[40000(ATS) + 21000(LTS)$
		$+ 139000(BTS)]\}\{KMCS\}$
TECHNICAL SUPPORT	$23.632(KLRS)(TSC)^{.485}(PL)^{.678}$	

APPENDIX D SYMBOL DEFINITION

<u>A</u>

AGEF	Age Factor
AMGC	First Unit Material, CFE, & Subcontract Cost for Guidance and Control Subsystem - Entry Vehicle (E/V).
AMGCM	First Unit Material, CFE, & Subcontract Cost for Guidance and Control Subsystem - Mission Module (M/M).
AMOBC	First Unit Material, CFE, & Subcontract Cost for Onboard Checkout Subsystem - E/V.
AMOBCM	First Unit Material, CFE, & Subcontract Cost for Onboard Checkout Subsystem - M/M.
AMTC	First Unit Material, CFE, & Subcontract Cost for Telecommunications Subsystem - E/V.
AMTCM	First Unit Material, CFE, & Subcontract Cost for Telecommunications Subsystem - M/M
ATS	Air Transport Switch.

<u>B</u>

BAL	Ballistic Configuration Switch
BAT	Energy in Watt-Hours per battery, E/V.
BATM	Energy in Watt-Hours per battery, M/M.
BMGC	Material, CFE, & Subcontract - Design & Development Cost for Guidance & Control Subsystem - E/V.
BMGCM	Material, CFE, & Subcontract - Design & Development Cost for Guidance & Control Subsystem - M/M.
BMOBC	Material, CFE, & Subcontract - Design & Development Cost for Onboard Checkout Subsystem - E/V.
BMOBCM	Material, CFE, & Subcontract - Design & Development Cost for Onboard Checkout Subsystem - M/M.
BMTC	Material, CFE, & Subcontract - Design & Development Cost for Telecommunications Subsystem - E/V.
BMTCM	Material, CFE, & Subcontract - Design & Development Cost for Telecommunications Subsystem - M/M.
BTS	Barge Transportation Switch.

C

CAHFC	Production labor cost of airdrop hardware final assembly and checkout.
CAHP	Production labor cost of airdrop hardware excluding final assembly and checkout.
CAHTS	Total cost of airdrop hardware Thermal/Structural group.
CAPSS	Production labor cost of airdrop hardware for non-structural subsystems.
CAPTS	Production labor cost of airdrop hardware for Thermal/Structural group.
CASE	Sustaining engineering labor cost for airdrop hardware.
CAST	Sustaining tooling labor cost for airdrop hardware.
CEDD	Prime Contractor Engineering E/V and M/M D&D Cost = CESRE + CESSRE + CESRM + CESSRM
CELUSE	Prime Contractor Engineering Design and Development Cost of Launch Upper Stages Engines
CESRE	Prime Contractor Engineering Design and Development Cost of E/V Thermal/Structure Group and Launch Upper Stage Tanks
CESRM	Prime Contractor Engineering Design and Development Cost of M/M Thermal/Structure Group
CESSRE	Prime Contractor Engineering D&D Cost of all non-structural subsystems - E/V
CESSRM	Prime Contractor Engineering D&D cost of all non-structural subsystems - M/M
CMCS	Material, CFE, and Subcontract first unit cost of the Crew Station, E/V.
CMDSRE	Material, CFE, and Subcontract Design & Development Cost of the Deorbit Solid Rocket Motor Subsystem - E/V
CMDSRM	Material, CFE, and Subcontract Design & Development Cost of the Deorbit Solid Rocket Motor Subsystem - M/M
CMEACE	Material, CFE, and Subcontract Design & Development Cost of the Entry Attitude Control Subsystem - E/V
CMECSE	Material, CFE, and Subcontract Design & Development Cost of the Environmental Control Subsystem - E/V
CMECSM	Material, CFE, and Subcontract Design & Development Cost of the Environmental Control Subsystem - M/M

CMFCE	Material, CFE, and Subcontract Design & Development Cost of the Fuel Cell Subsystem E/V
CMFCM	Material, CFE, and Subcontract Design & Development Cost of the Fuel Cell Subsystem - M/M
CMGCE	Material, CFE, and Subcontract Design & Development Cost of the Guidance Control Subsystem - E/V
CMGCM	Material, CFE, and Subcontract Design & Development Cost of the Guidance and Control Subsystem - M/M
CMHP	Material, CFE, and Subcontract first unit cost of the Hydraulics and Pneumatics.
CMLA	Material CFE, and Subcontract first unit cost of the Landing Assist Solid Rocket Motor - E/V.
CMLAE	Material, CFE, and Subcontract Design & Development Cost of the Landing Assist Solid Rocket Motor Subsystem - E/V
CMLESE	Material, CFE, and Subcontract Design & Development cost of the Launch Escape Motors Subsystem - E/V
CMLESM	Material, CFE, and Subcontract Design & Development cost of the Launch Escape Motors Subsystem - M/M
CMLG	Material, CFE, and Subcontract first unit cost of the Landing Gear.
CMMOME	Material, CFE, and Subcontract Design & Development cost of the Main Orbital Maneuver Subsystem - E/V
CMMOMM	Material, CFE, and Subcontract Design & Development Cost of the Main Orbital Maneuver Subsystem - M/M
CMO	Material, CFE, and Subcontract first unit cost of the Ordnance, E/V
CMOBCE	Material, CFE, and Subcontract Design & Development cost of the Onboard Checkout Subsystem - E/V
CMOBCM	Material, CFE, and Subcontract Design & Development cost of the Onboard Checkout Subsystem - M/M
CMP	Material, CFE, and Subcontract first unit cost of the Parachute, E/V.
CMPCE	Material, CFE, and Subcontract Design & Development cost of the Recovery Parachute Subsystem - E/V

CMRSSE	Material, CFE, and Subcontract Design & Development cost of the Reactant Supply Subsystem - E/V
CMRSSM	Material, CFE, and Subcontract Design & Development cost of the Reactant Supply Subsystem - M/M
CMSAC	Material, CFE, and Subcontract first unit cost of the Aerodynamic Control Surfaces.
CMSCS	Material, CFE, and Subcontract first unit cost of Crew Section Structure.
CMSGE	First Unit Material Costs of E/V Thermal/Structure Group
CMSW	Material, CFE, and Subcontract first unit cost of the Sailwing
CMSWE	Material, CFE, and Subcontract Design & Development cost of the Recovery Sailwing Subsystem - E/V
CMRSYS	Material, CFE, and Subcontract Design & Development cost of the non-structural Subsystems, E/V & M/M total
CMSSE	First Unit Material, CFE, Subcontract costs of the Entry Vehicle
CMTCE	Material, CFE, and Subcontract Design & Development cost of the Telecommunications Subsystem - E/V
CMTCM	Material, CFE, and Subcontract Design & Development cost of the Telecommunications Subsystem - M/M
CMTPA	Material, CFE, and Subcontract first unit cost of the Ablative Thermal Protection.
CMTPR	Material, CFE, and Subcontract first unit cost of the Radiative Thermal Protection.
CMTSTR	Material, CFE, and Subcontract First Unit Cost of Thermal/Structure Group and Launch Upper Stage Tanks E/V & M/M.
CMTSYS	Material, CFE, and Subcontract First Unit Cost of non-structural Subsystems E/V & M/M
CMVME	Material, CFE, and Subcontract Design and Development cost of the Vernier Maneuver Subsystem - E/V
CMVMM	Material, CFE, and Subcontract Design and Development cost of the Vernier Maneuver Subsystem - M/M
COPAM	Operational Labor Cost of AGE Maintenance - S/C
COPFM	Operational Labor Cost of Facility Maintenance - S/C
COPLAS	Launch Area Support Labor Cost
CPCS	First Unit Production cost of the Crew Station, E/V

CPE	First Unit Production Labor Cost (excludes Final Assembly and Checkout); E/V. CPE = CPSE + CPSYSE
CPFC	First Unit Production Cost of Final Assembly and Checkout - E/V
CPFCM	First Unit Production Cost of Final Assembly and Checkout - M/M
CPHP	First Unit Production cost of the Hydraulics and Pneumatics.
CPLA	First Unit Production cost of the Landing Assist Solid Rocket.
CPLG	First Unit Production cost of the Landing Gear.
CPM	Prime Contractor First Unit Production Labor Cost (excludes Final Assembly and Checkout) - M/M. CPM = CPSM + CPSYSM
CPO	First Unit Production cost of the Ordnance, E/V.
CPP	First Unit Production cost of the Parachute.
CPRFLA	RDT&E Labor Cost for Launch Site Facility Activation
CPRFRS	RDT&E Labor Cost for Recovery Site Facilities
CPSAC	First Unit Production cost of the Aerodynamic Control Surfaces.
CPSCS	First Unit Production cost of the Crew Section Structure.
CPSGE	First Unit Production Costs of the E/V Thermal/Structural Group
CPSE	First Unit Production Cost of Thermal/Structure Group and Launch Upper Stage tanks - E/V.
CPSM	First Unit Production Cost of Thermal/Structure Group - M/M
CPSW	First Unit Production cost of the Sailwing.
CPSYSE	First Unit Production Cost of non-structural Subsystems - E/V
CPSYSM	First Unit Production Cost of non-structural Subsystems - M/M
CPTPA	First Unit Production cost of the Ablative Thermal Protection
CPTPR	First Unit Production cost of the Radiative Thermal Protection
CRAGR	RDT&E Total Recurring Initial AGE Cost
CRE	Total RDT&E Prime Contractor Engineering Cost - S/C
CRFAC	RDT&E Facility Cost
CRPLSA	RDT&E Launch Site Peculiar AGE Labor Cost
CRSSF	Labor Cost of Remote Site Static Fire Testing of the Launch Upper Stage Propulsion
CSEE	First Unit Sustaining Engineering Cost - E/V
CSEM	First Unit Sustaining Engineering Cost - M/M
CSTE	First Unit Sustaining Tooling Cost - E/V
CSTM	First Unit Sustaining Tooling Cost - M/M
CTP	First Unit Production Cost - S/C = CPSE + CPSM + CPSYSE + CPSYSM + CPFC + CPFCM

CTRA	Design and Development Tooling Cost of the Simple Adapter Structure
CTRCPE	Design and Development Tooling Cost of the Cargo/Propulsion Section Structure - E/V
CTRCPM	Design and Development Tooling Cost of the Cargo/Propulsion Section Structure - M/M
CTRCSE	Design and Development Tooling Cost of the Crew Section Structure
CTRLG	Design and Development Tooling Cost of the Landing Gear Subsystem
CTRLT	Design and Development Tooling Cost of the Launch Escape Tower Subsystem
CTRTE	D&D Tooling Cost of the Launch Upper Stage External Propellant Tanks
CTRTI	D&D Tooling Cost of the Launch Upper Stage Internal Propellant Tanks
CTRTPE	D&D Tooling Cost for the Ablative Thermal Protection Subsystem

E

EKWH	Total energy in kilowatt hours of the fuel cell system in the E/V.
EKWHM	Total energy in kilowatt hours of the fuel cell system in the M/M.
E2S	Existing recovery site network switch.

F

FECABL	Thrust in lbs. of Entry Attitude Control Subsystem pressure fed ablative cooled engine
FECRAD	Thrust in lbs. of Entry Attitude Control Subsystem pressure fed radiation cooled engine
FLRGC	Thrust in lbs. of regenerative pump fed cryogenic engine - Launch Upper Stage Subsystem
FLRGS	Thrust in lbs. of regenerative pump fed storable engine - Launch Upper Stage Subsystem
FMABL	Thrust in lbs. of pressure fed storable ablative engine - Main Orbital Maneuver Subsystem - E/V
FMABLM	Thrust in lbs. of pressure fed storable ablative engine - Main Orbital Maneuver Subsystem - M/M
FMRGC	Thrust in lbs. of pump fed cryogenic regenerative engine - Main Orbital Maneuver Subsystem - E/V
FMRGCM	Thrust in lbs. of pump fed cryogenic regenerative engine - Main Orbital Maneuver Subsystem - M/M

FMRGS	Thrust in lbs. of pump fed storable regenerative engine - Main Orbital Maneuver Subsystem - E/V
FMRGSM	Thrust in lbs. of pump fed storable regenerative engine - Main Orbital Maneuver Subsystem - M/M
FVDAB	Thrust in lbs. of pressure fed storable ablative secondary engine- Vernier Maneuver Subsystem - E/V
FVDABM	Thrust in lbs. of pressure fed storable ablative secondary engine - Vernier Maneuver Subsystem - M/M
FVDRA	Thrust in lbs. of pressure fed storable radiation secondary engine - Vernier Maneuver Subsystem - E/V
FVDRAM	Thrust in lbs. of pressure fed storable radiation secondary engine - Vernier Maneuver Subsystem - M/M
FVOAB	Thrust in lbs. of pressure fed storable ablative main engine - Vernier Maneuver Subsystem - E/V
FVOABM	Thrust in lbs. of pressure fed storable ablative main engine - Vernier Maneuver Subsystem - M/M
FVORA	Thrust in lbs. of pressure fed storable radiation main engine - Vernier Maneuver Subsystem - E/V
FVORAM	Thrust in lbs. of pressure fed storable radiation main engine - Vernier Maneuver Subsystem - M/M
H	
HFT	Hot Fire Acceptance Test Switch
I	
IBV	Ballistic configuration switch for reuse modes D, E, & F
ILB	Lifting Body configuration switch for reuse modes D, E, & F
ITDO	Total impulse in lb-sec. of one solid rocket motor - Deorbit Subsystem - E/V
ITDOM	Total impulse in lb-sec. of one solid rocket motor - Deorbit Subsystem - M/M
ITLA	Total impulse in lb-sec. of one solid rocket motor - Landing Assist Subsystem - E/V
ITLEH	Total impulse in lb-sec. of one solid rocket motor - High Altitude Launch Escape - E/V
ITLEL	Total impulse in lb-sec. of one solid rocket motor - Low Altitude Launch Escape - E/V

ITLELM	Total impulse in lb-sec. of one solid rocket motor - Low Altitude Launch Escape - M/M
<u>K</u>	
KACPE	Access Area Factor - Cargo/Propulsion Section - E/V - Used in Design & Development Engineering
KACPME	Access Area Factor - Cargo/Propulsion Section - M/M - Used in Design & Development Engineering
KACPMP	Access Area Factor - Cargo/Propulsion Section - M/M - Used in First Unit Production & Material, CFE, & Subcontract
KACPMT	Access Area Factor - Cargo/Propulsion Section - M/M - Used in Design & Development Tooling.
KACPP	Access Area Factor - Cargo/Propulsion Section - E/V - Used in First Unit Production & Material, CFE, & Subcontract
KACPT	Access Area Factor - Cargo/Propulsion Section - E/V - Used in Design Development Tooling
KACSE	Access Area Factor - Crew Section - E/V - Used in Design & Development Engineering
KACSP	Access Area Factor - Crew Section - E/V - Used in First Unit Production
KACST	Access Area Factor - Crew Section - E/V - Used in Design & Development Tooling
KCCP	Configuration Complexity Factor - Cargo/Propulsion Section - E/V - Used in Design & Development Engineering
KCCS	Configuration Complexity Factor - Crew Section - E/V - Used in Design & Development Engineering
KCT	Configuration Complexity Factor - E/V - Used in Design & Development Tooling
KCWT	Wind Tunnel vehicle configuration complexity factor
KDCP	Density Factor - Cargo/Propulsion Section - E/V
KDCPM	Density Factor - Cargo/Propulsion Section - M/M
KDCS	Density Factor - Crew Section - E/V
KECON	Economic Escalation Factor
KECSC	Environmental Control Subsystem - Cryogenic gas indicator and percent of subsystem in E/V

KECSCM	Environmental Control Subsystem - Cryogenic gas indicator and percent of subsystem in M/M
KECSS	Environmental Control Subsystem - Storable gas indicator and percent of subsystem in E/V
KECSSM	Environmental Control Subsystem - Storable gas indicator and percent of subsystem in M/M
KENGR	Engineering Labor Rate - Dollars per manhour
KLRS	Remote Site Labor Rate - Dollars per manhour
KMACSP	Type of Material and Construction complexity Factor - Aerodynamic Control Surfaces
KMAP	Type of Material and Construction Complexity Factor - Simple Adapter
KMCPMP	Type of Material and Construction Complexity Factor - Cargo/ Propulsion Section - M/M
KMCPP	Type of Material and Construction Complexity Factor - Cargo/ Propulsion Section - E/V
KMCS	Material, CFE, & Subcontract Economic Escalation Factor
KMCSP	Type of Material and Construction Complexity Factor - Crew Section - E/V
KMTPA	Type of Material Complexity Factor - Ablative Thermal Protection Subsystem - E/V.
KMTPR	Type of Material Complexity Factor - Radiative Thermal Protection Subsystem - E/V.
KPRL	Type of propellant factor - cost per pound of thrust for varying propellants. Used in Design and Development - Launch Upper Stage.
KPRL1	Type of propellant factor - cost per pound of thrust for varying propellants. Used in Static Fire Qualification Test.
KPRL2	Type of propellant factor - cost per pound of thrust for varying propellants. Used in Static Fire Acceptance Test.
KPRLC	Type of propellant factor - differences in first unit cost between cryogenic engines. LOX/LH_2 vs. F_2/LH_2
KPRLUC	Type of propellant factor - differences in Design & Development cost between cryogenic engines. LOX/LH_2 vs. F_2/LH_2
KPRMF	Type of propellant factor - storable or cryogenic, for fuel tank cost - Main Orbital Maneuver - First Unit - E/V.
KPRMFM	Type of propellant factor - storable or cryogenic, for fuel tank cost - Main Orbital Maneuver - First Unit M/M.

KPRMO	Type of propellant factor storable or cryogenic, for oxidizer tank cost - Main Orbital Maneuver - First Unit - E/V.
KPRMOM	Type of propellant factor - storable or cryogenic, for oxidizer tank cost - Main Orbital Maneuver - First Unit - M/M.
KPROD	Production Labor Rate - Dollars per Manhour
KPS	Type of propellant used in the cargo/propulsion section structure - E/V.
KPT	Type of propellant used in the Launch Upper Stage Propellant Tanks.
KRED	Redundancy factor - Entry Attitude Control Subsystem
KSA	Panel Shape Complexity Factor - Ablative Thermal Protection Subsystem.
KSR	Panel Shape Complexity Factor - Radiative Thermal Protection Subsystem.
KTOOL	Tooling Labor Rate - Dollars per manhour.

L

LEVDAM	Material, CFE, & Subcontract - Design & Development - Ablative secondary engine locator - Vernier Maneuver - M/M.
LEVDRM	Material, CFE, & Subcontract - Design & Development - Radiation secondary engine locator - Vernier Maneuver - M/M.
LEVOAM	Material, CFE, & Subcontract - Design & Development - Ablative secondary engine locator - Vernier Maneuver - M/M.
LEVORM	Material, CFE, & Subcontract - Design & Development - Radiation secondary engine locator - Vernier Maneuver - M/M.
LLM	Land landing mode switch.
LREECA	Material, CFE, & Subcontract - Design & Development - Ablative engine locator - Entry Attitude Control.
LREECR	Material, CFE, & Subcontract - Design & Development - Radiation engine locator - Entry Attitude Control
LREMA	Material, CFE, & Subcontract - Design & Development - Ablative engine locator - Main Orbital Maneuver - E/V.

LREMAM	Material, CFE, & Subcontract - Design & Development - Ablative engine locator - Main Orbital Maneuver - M/M.
LREMC	Material, CFE, & Subcontract - Design & Development - regenerative cryogenic engine locator - Main Orbital Maneuver - E/V.
LREMCM	Material, CFE, & Subcontract - Design & Development - regenerative cryogenic engine locator - Main Orbital Maneuver - M/M.
LREMS	Material, CFE, & Subcontract - Design & Development - regenerative storable engine locator - Main Orbital Maneuver - E/V.
LREMSM	Material, CFE, & Subcontract - Design & Development - regenerative storable engine locator - Main Orbital Maneuver - M/M.
LREVDA	Material, CFE, & Subcontract - Design & Development - ablative secondary engine locator - Vernier Maneuver - E/V.
LREVDR	Material, CFE, & Subcontract - Design & Development - ablative secondary engine locator - Vernier Maneuver - E/V.
LREVOA	Material, CFE, & Subcontract - Design & Development - ablative main engine locator - Vernier Maneuver - E/V.
LREVOR	Material, CFE, & Subcontract - Design & Development - radiation main engine locator - Vernier Maneuver - E/V.
LSTOA	Airdrop system test operations locator.
LTS	Land Transportation Switch.

<u>M</u>

M	Number of men in spacecraft.
MBV	Ballistic configuration switch - reuse modes A, B, & C.
MLB	Lifting Body configuration switch - reuse modes A, B, & C.
MT	Mission duration in days.

<u>N</u>

NB	Number of batteries in E/V.
NBM	Number of batteries in M/M.
NE	Number of engines in integral propulsion.
NEECAB	Number of ablative engines in the Entry Attitude Control Subsystem.
NEECRA	Number of radiation engines in the Entry Attitude Control Subsystem.
NELRGC	Number of regenerative cryogenic engines in the Launch Upper Stage Subsystem.

NELRGS	Number of regenerative storable engines in the Launch Upper Stage Subsystem.
NEMAB	Number of ablative engines in the Main Orbital Maneuver Subsystem - E/V.
NEMABM	Number of ablative engines in the Main Orbital Maneuver Subsystem - M/M.
NEMRCM	Number of regenerative cryogenic engines in the Main Orbital Maneuver Subsystem - M/M.
NEMRGC	Number of regenerative cryogenic engines in the Main Orbital Maneuver Subsystem - E/V.
NEMRGS	Number of regenerative storable engines in the Main Orbital Maneuver Subsystem - E/V.
NEMRSM	Number of regenerative storable engines in the Main Orbital Maneuver Subsystem - M/M.
NEVDAB	Number of ablative secondary engines in the Vernier Maneuver Subsystem - E/V.
NEVDAM	Number of ablative secondary engines in the Vernier Maneuver Subsystem - M/M.
NEVDRA	Number of radiative secondary engines in the Vernier Maneuver Subsystem - E/V.
NEVDRM	Number of radiative secondary engines in the Vernier Maneuver Subsystem - M/M.
NEVOAB	Number of ablative main engines in the Vernier Maneuver Subsystem - E/V.
NEVOAM	Number of ablative main engines in the Vernier Maneuver Subsystem - M/M.
NEVORA	Number of radiation main engines in the Vernier Maneuver Subsystem - E/V.
NEVORM	Number of radiation main engines in the Vernier Maneuver Subsystem - M/M.
NFC	Number of fuel cells in the E/V.
NFCM	Number of fuel cells in the M/M.
NMDO	Number of solid rocket motors in the Deorbit Subsystem - E/V.
NMDOM	Number of solid rocket motors in the Deorbit Subsystem - M/M.
NMLA	Number of solid rocket motors in the Landing Assist Subsystem.
NMLEH	Number of solid rocket motors in the High Altitude Launch Escape Subsystem.
NMLEL	Number of solid rocket motors in the Low Altitude Launch Escape Subsystem - E/V.
NMLELM	Number of solid rocket motors in the Low Altitude Launch Escape Subsystem - M/M.
NR	Number of refurbishments.

NS	Number of existing recovery sites.
NTEAC	Number of fuel and oxidizer tanks in the Entry Attitude Control Subsys.
NTEXT	Number of external tanks in the Launch Upper Stage Subsystem.
NTMDF	Number of secondary fuel tanks in the Main Orbital Maneuver Subsys. - E/V.
NTMDFM	Number of secondary fuel tanks in the Main Orbital Maneuver Subsys. - M/M.
NTMDO	Number of secondary oxidizer tanks in the Main Orbital Maneuver Subsystem - E/V.
MTMDOM	Number of secondary oxidizer tanks in the Main Orbital Maneuver Subsystem - M/M.
NTMOF	Number of main fuel tanks in the Main Orbital Maneuver Subsys. - E/V.
NTMOFM	Number of main fuel tanks in the Main Orbital Maneuver Subsys. - M/M.
NTMOO	Number of main oxidizer tanks in the Main Orbital Maneuver Subsys. - E/V.
NTMOOM	Number of main oxidizer tanks in the Main Orbital Maneuver Subsys. - M/M.
NTVMD	Number of secondary fuel and oxidizer tanks in the Vernier Maneuver Subsystem - E/V.
NTVMDM	Number of secondary fuel and oxidizer tanks in the Vernier Maneuver Subsystem - M/M.
NTVMO	Number of main fuel and oxidizer tanks in the Vernier Maneuver Subsystem - E/V.
NTVMOM	Number of main fuel and oxidizer tanks in the Vernier Maneuver Subsystem - M/M.
<u>P</u>	
PCLRGC	Launch Upper Stage Subsystem indicator for high chamber pressure cryogenic engines.
PCLRGS	Launch Upper Stage Subsystem indicator for high chamber pressure storable engines.
PKW	Power output per fuel cell - kilowatts - E/V.
PKWM	Power output per fuel cell - kilowatts - M/M.
PL	Operational program life in years from the first launch to the last.
PSA	Ablative average panel size in square feet - Thermal Protection Subsys.
PSR	Radiative average panel size in square feet - Thermal Protection Sys.
<u>Q</u>	
QA1	Quantity of airdrop test vehicles.
QAGE1	Quantity of equivalent sets of initial AGE.
QAGE2	Quantity of equivalent sets of additional AGE.

QF1	Quantity of boosted flight test vehicles.
QF2	Quantity of boosted flight test flights.
QG1	Quantity of ground test vehicles - E/V.
QG2	Quantity of ground test vehicles - M/M.
QI1	Total quantity of boosted flight test and investment vehicles.
QI2	Total quantity of boosted flight test and investment flights.
S	
SWTPA	Total wetted area in sq. feet of ablative thermal protection panels.
SWTPR	Total wetted area in sq. feet of radiative thermal protection panels.
T	
TDS	Test deletion switch REFPC = 3, TDS = 1; REFPC ≠ 3, TDS = 0.
TSC	Total Spacecraft First Unit cost (includes sustaining engr., sustaining tooling, production, and material, CFE, subcontract.
U	
USP	Integral Upper Stage Propulsion Switch.
V	
VLM	Vertical landing mode switch.
VMDF	Volume of one secondary fuel tank in the Main Orbital Maneuver Subsystem - E/V, Cubic Feet
VMDFM	Volume of one secondary fuel tank in the Main Orbital Maneuver Subsystem - M/M, Cubic Feet
VMDOX	Volume of one secondary oxidizer tank in the Main Orbital Maneuver Subsystem - E/V, Cubic Feet
VMDOXM	Volume of one secondary oxidizer tank in the Main Orbital Maneuver Subsystem - M/M, Cubic Feet
VMOF	Volume of one main fuel tank in the Main Orbital Maneuver Subsystem - E/V, Cubic Feet
VMOFM	Volume of one main fuel tank in the Main Orbital Maneuver Subsystem - M/M, Cubic Feet
VMOOX	Volume of one main oxidizer tank in the Main Orbital Maneuver Subsystem - E/V, Cubic Feet
VMOOXM	Volume of one main oxidizer tank in the Main Orbital Maneuver Subsystem - M/M, Cubic Feet
VS	Staging Velocity, feet per second
VTEAC	Volume of one fuel or oxidizer tank in the Entry Attitude Control Subsystem, Cubic Feet

VTVMD	Volume of one secondary fuel or oxidizer tank in the Vernier Maneuver Subsystem - E/V, Cubic Feet
VTVMDM	Volume of one secondary fuel or oxidizer tank in the Vernier Maneuver Subsystem - M/M, Cubic Feet
VTVMO	Volume of one main fuel or oxidizer tank in the Vernier Maneuver Subsystem - E/V, Cubic Feet
VTVMOM	Volume of one main fuel or oxidizer tank in the Vernier Maneuver Subsystem - M/M, Cubic Feet

W

WB	Battery weight, pounds - E/V.
WBM	Battery weight, pounds - M/M.
WCDPC	Total Weight in pounds of the E/V at Parachute deployment.
WCDSW	Total Weight in pounds of the E/V at Sailwing deployment.
WCS	Weight in pounds of Crew Station Subsystem - E/V.
WCSM	Weight in pounds of Crew Station Subsystem - M/M.
WDEV	Total Dry weight in pounds of Entry Vehicle subsystems and structure.
WDMM	Total Dry weight in pounds of Mission Module subsystems and structure.
WDO	Dry weight in pounds of Solid Deorbit Subsystem - E/V.
WDOM	Dry weight in pounds of Solid Deorbit Subsystem - M/M.
WEAC	Dry weight in pounds of Entry Attitude Control Subsystem.
WECLVM	Dry weight in pounds of Entry Attitude Control Subsystem-lines, valves, and miscellaneous.
WECS	Dry weight in pounds of Environmental Control Subsystem - E/V
WECSM	Dry weight in pounds of Environmental Control Subsystem - M/M
WEPD	Weight in pounds of Electrical Power Distribution Subsystem - E/V.
WEPDM	Weight in pounds of Electrical Power Distribution subsystem - M/M.
WFC	Weight in pounds of Fuel Cell Subsystem - E/V.
WFCM	Weight in pounds of Fuel Cell Subsystem - M/M.
WFE	Dry weight in pounds of Furnishings & Equipment subsystem.
WFOC	Bulk weight of FLOX/CH4 in pounds per launch.
WGC	Weight in pounds of the Guidance & Control Subsystem - E/V.
WGCM	Weight in pounds of the Guidance & Control Subsystem - M/M.
WHPN	Weight in pounds of the Hydraulics and Pneumatics Subsystem.
WLA	Dry weight in pounds of the Landing Assist Subsystem.

WLESE	Dry weight in pounds of the Launch Escape Motor Subsystem - E/V.
WLESEM	Dry weight in pounds of the Launch Escape Motor Subsystem - M/M.
WLEXT	Dry weight in pounds of the one external tank in the Launch Upper Stage Subsystem. (Additional tanks are exact duplicates.)
WLFH	Bulk weight of F_2/H_2 in pounds per launch.
WLG	Weight in pounds of the Landing Gear Subsystem.
WLINTS	Dry weight in pounds of the spherical tank in the Launch Upper Stage Subsystem.
WLINTT	Dry weight in pounds of the torroidal tank in the Launch Upper Stage Subsystem.
WLLVM	Dry weight in pounds of the lines, valves, & miscellaneous of the Launch Upper Stage Subsystem.
WLOH	Bulk weight of O_2/H_2 in pounds per launch.
WLUSE	Dry weight in pounds of the engine, lines, valves, & miscellaneous of the Launch Upper State Subsystem.
WMLVM	Dry weight in pounds of the lines, valves, & miscellaneous of the Main Maneuver Subsystem - E/V.
WMLVMM	Dry weight in pounds of the lines, valves, & miscellaneous of the Main Maneuver Subsystem - M/M.
WMOM	Dry weight in pounds of the Main Maneuver Subsystem - E/V.
WMOMM	Dry weight in pounds of the Main Maneuver Subsystem - M/M.
WOBC	Weight in pounds of the Onboard Checkout Subsystem - E/V.
WOBCM	Weight in pounds of the Onboard Checkout Subsystem - M/M.
WORD	Weight in pounds of the Ordnance Subsystem - E/V.
WORDM	Weight in pounds of the Ordnance Subsystem - M/M.
WPLUS	Total weight in pounds of the propellant in the Launch Upper Stage Subsystem.
WRPC	Weight in pounds of the Parachute Subsystem.
WRSS	Dry weight in pounds of the Reactant Supply Subsystem - E/V.
WRSSM	Dry weight in pounds of the Reactant Supply Subsystem - M/M.
WRSW	Weight in pounds of the Sailwing Subsystem.
WSA	Weight in pounds of the simple adapter structure - includes mounting structure.
WSACSP	Weight in pounds of the Aerodynamic Control Surfaces Structure - excludes all thermal protection.

WSCPET	Weight in pounds of the Cargo/Propulsion Section Structure - E/V - excludes ablative thermal protection, includes radiative thermal protection, and mounting structure.
WSCPM	Weight in pounds of the Cargo/Propulsion Section Structure - M/M, includes mounting structure
WSCPP	Weight in pounds of the Cargo/Propulsion Section Structure - E/V - excludes all thermal protection & aerodynamic control surfaces, includes mounting structure.
WSCSET	Weight in pounds of the Crew Section Structure - excludes ablative thermal protection, includes radiative thermal protection and mounting structure.
WSCSP	Weight in pounds of the Crew Section Structure - excludes all thermal protection and aerodynamic control surfaces, includes mounting structure.
WSLET	Weight in pounds of the launch escape tower structure.
WSTO	Bulk weight of NTO/A-50 in pounds per launch.
WT	Launch Vehicle thrown weight capability in thousands of pounds (Due East ETR Launch, i = 28.5°)
WTC	Weight in pounds of the Telecommunications Subsystem - E/V.
WTCM	Weight in pounds of the Telecommunications Subsystem - M/M.
WVLVMM	Dry weight in pounds of the lines, valves, & miscellaneous of the Vernier Maneuver Subsystem - M/M.
WVM	Dry weight in pounds of the Vernier Maneuver Subsystem - E/V.
WVMLVM	Dry weight in pounds of the lines, valves & miscellaneous of the Vernier Maneuver Subsystem - E/V.
WVMM	Dry weight in pounds of the Vernier Maneuver Subsystem - M/M.
WWC	Dry weight in pounds of the Water Cooling Subsystem.
X	
XLC	Learning curve exponent (eg. 85% L.C. exponent is .766).